Small Dots Make it Big: Studying Collective Phenomena in Arrays of Superconducting Islands

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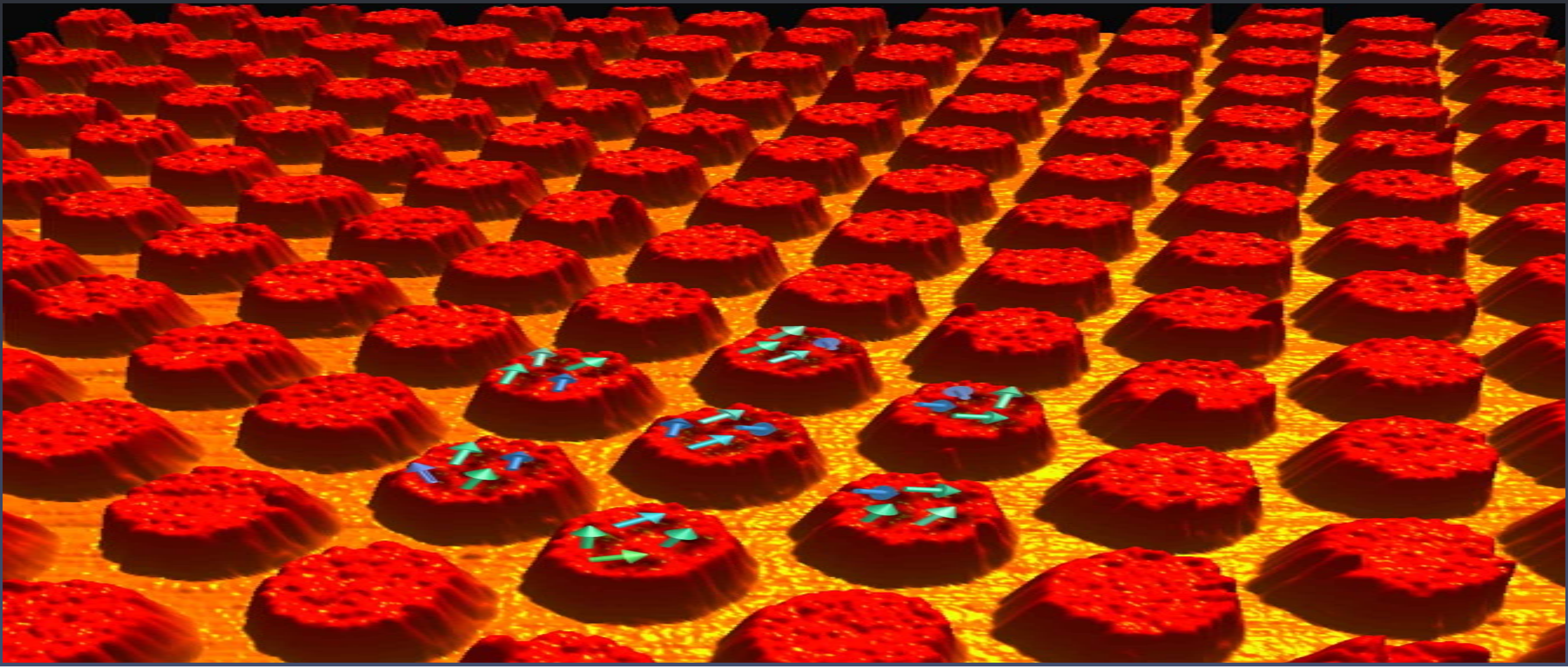
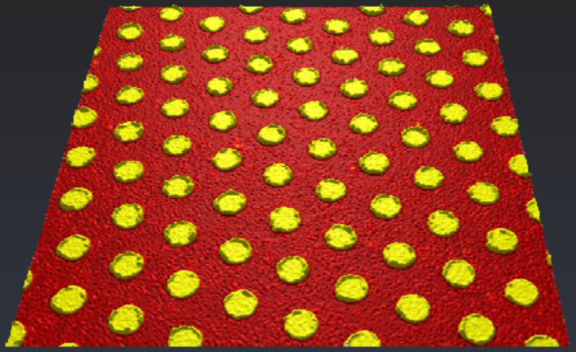
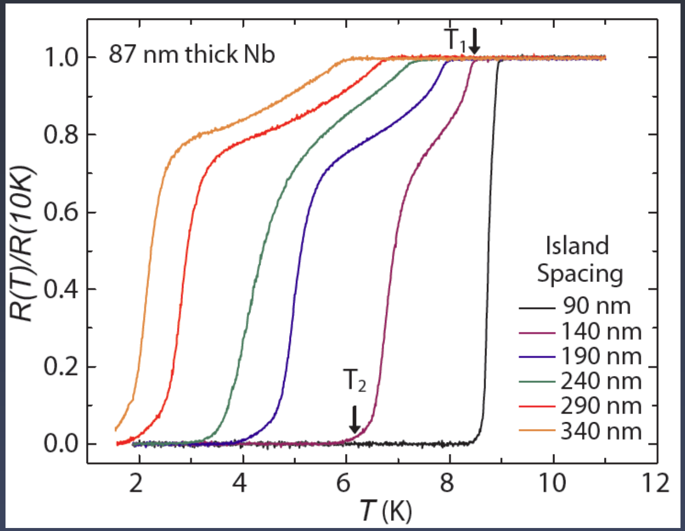


Outline

"Studying Collective Phenomena in Arrays of Superconducting Islands"

- Collective Phenomena
- Superconductivity
- Coupled superconducting islands
- 2D metallic states, vortex interactions





<u>Punchline</u>: Island arrays are a model system for studying parameters relevant to collective behavior

Collective Phenomena:

Interactions between particles in multi-particle system leads to new phases, whose behavior is different from that of individual particles

A “wave” of people in a stadium

→ cognitive, visual, motional

Ant bridge

→ touch, smell, “swarm rules”

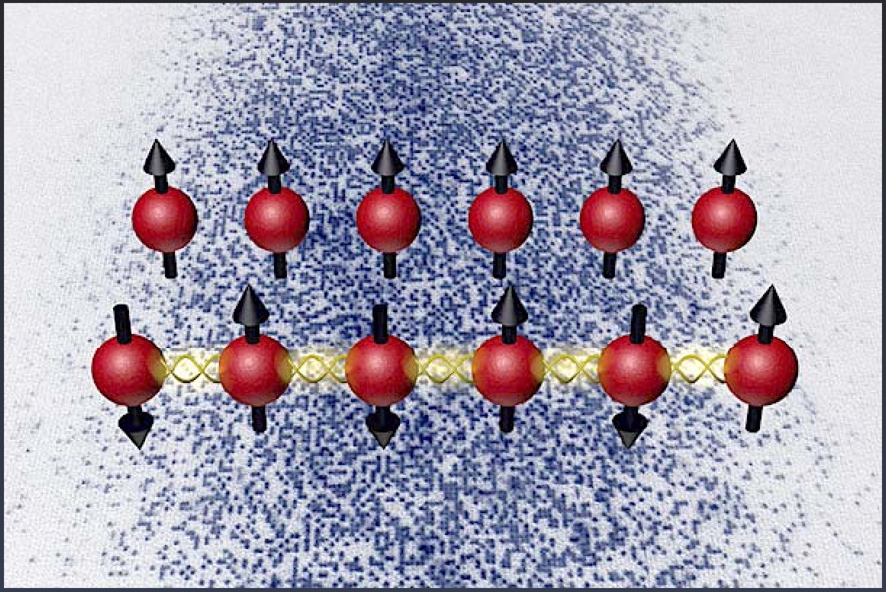
Collective Phenomena:

Interactions between particles in multi-particle system leads to new phases, whose behavior is different from that of individual particles

Magnetism

→ dipole interactions (spin/orbital)

- Ferromagnetism
- Anti-Ferromagnetism
- Spin Waves

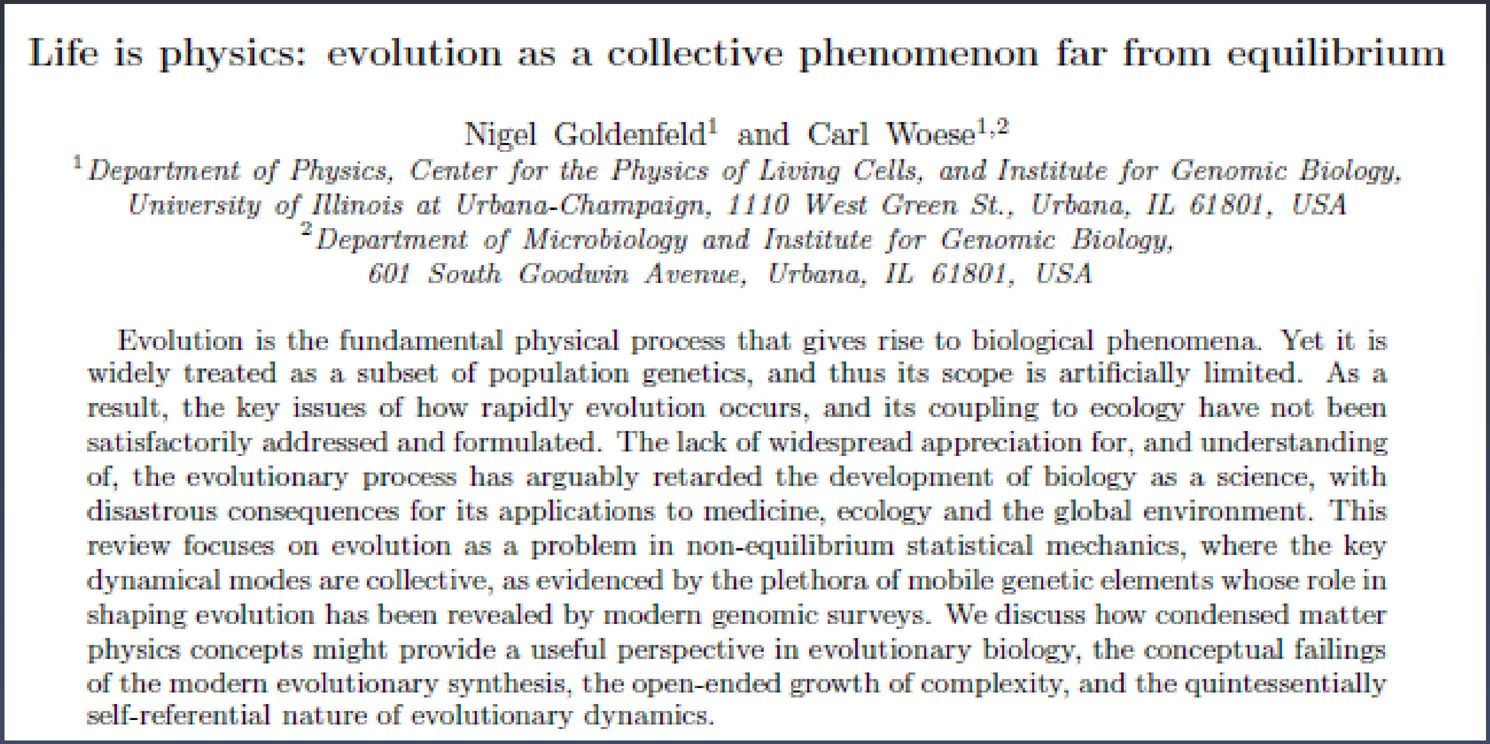


Collective Phenomena:

Interactions between particles in multi-particle system leads to new phases, whose behavior is different from that of individual particles

→ appear in many systems: insects, internet, crowds, materials, genetics

→ often complex, difficult to predict from individual components



Life is physics: evolution as a collective phenomenon far from equilibrium

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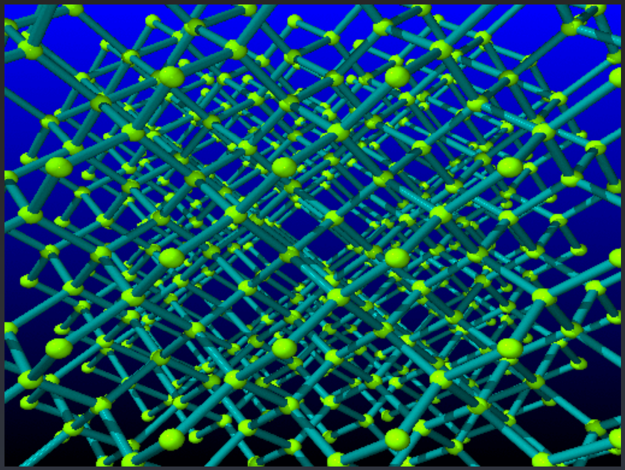
Evolution is the fundamental physical process that gives rise to biological phenomena. Yet it is widely treated as a subset of population genetics, and thus its scope is artificially limited. As a result, the key issues of how rapidly evolution occurs, and its coupling to ecology have not been satisfactorily addressed and formulated. The lack of widespread appreciation for, and understanding of, the evolutionary process has arguably retarded the development of biology as a science, with disastrous consequences for its applications to medicine, ecology and the global environment. This review focuses on evolution as a problem in non-equilibrium statistical mechanics, where the key dynamical modes are collective, as evidenced by the plethora of mobile genetic elements whose role in shaping evolution has been revealed by modern genomic surveys. We discuss how condensed matter physics concepts might provide a useful perspective in evolutionary biology, the conceptual failings of the modern evolutionary synthesis, the open-ended growth of complexity, and the quintessentially self-referential nature of evolutionary dynamics.

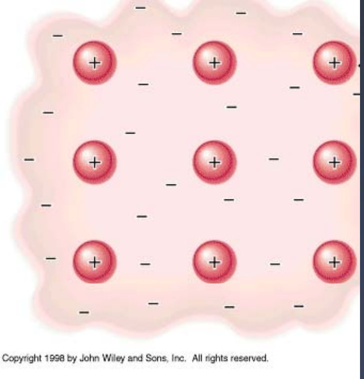
Solid state systems are inherently correlated, multi-particle

1 cm^3 of matter = 10^{23} atoms, electrons



Charge interactions lead to well-known phases:

-crystals
-metals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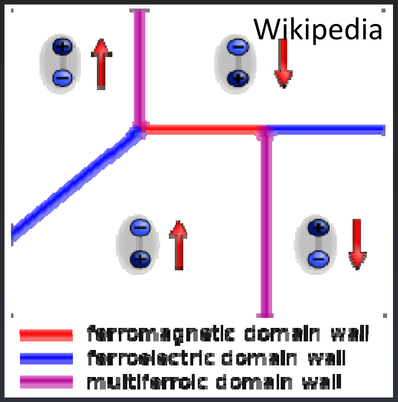
The “extra” electrons in metals can be considered to move freely as a non-interacting “free electron gas”

Charge, Spin, & Lattice interactions can lead to more interesting phases …

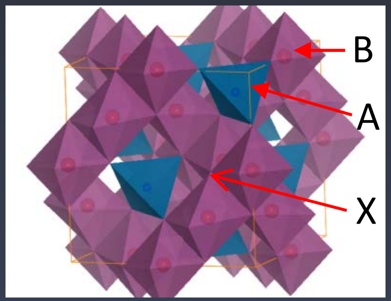
Examples of collective electronic effects

- Magnetism
- Multiferroics: Spin+charge order
- Frustrated crystals
- 1D: spin-charge separation
- Superconductivity



Wikipedia

e.g., $BaTiO_3$, $BiFeO_3$, $TbMnO_3$, …

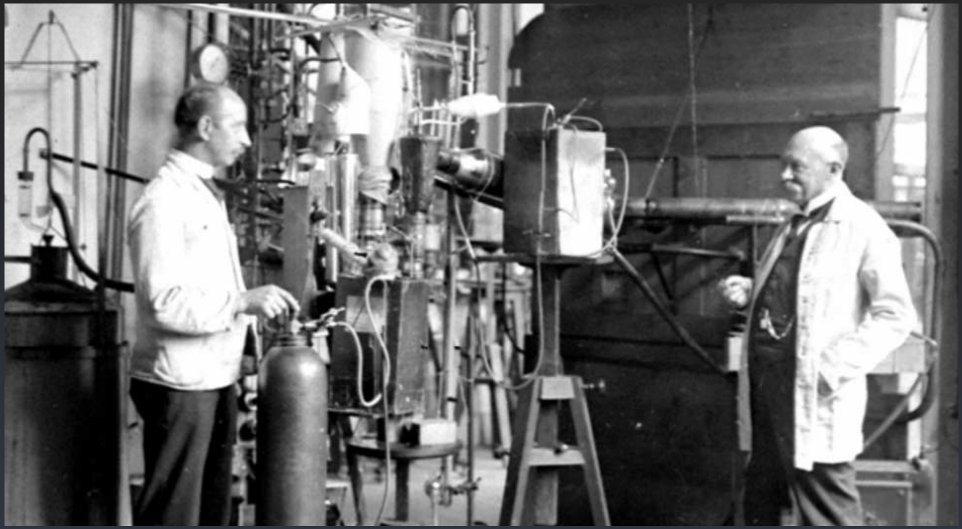


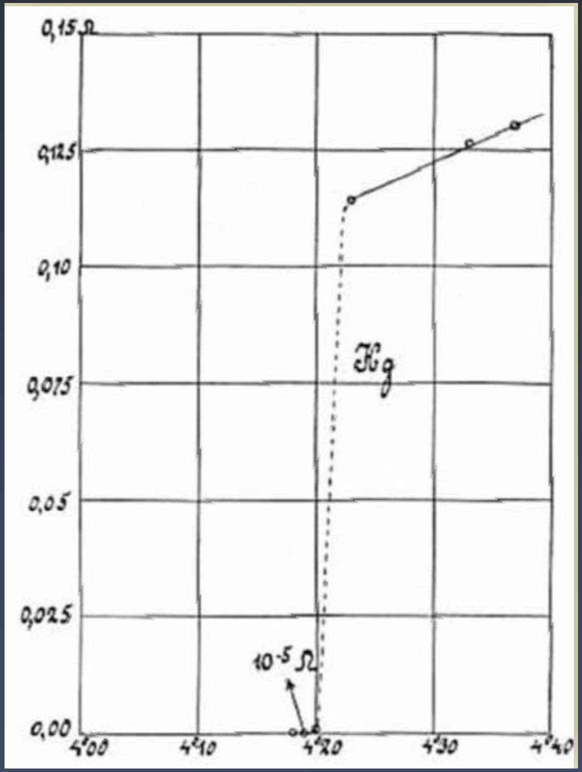
Spinel AB_2X_4:
B geometrically frustrated
(e.g., $CoAl_2O_4$, $FeCrO_4$)

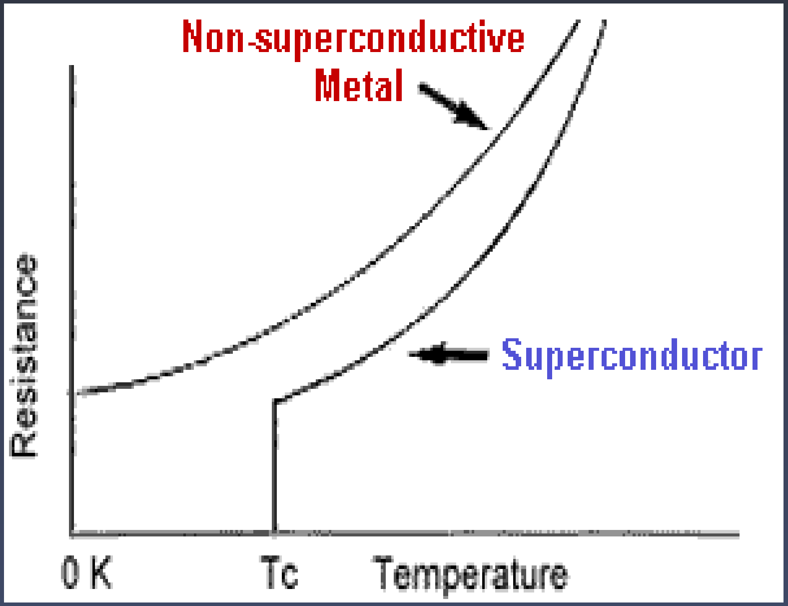
→ Many of these behaviors are useful in functional devices
→ Novel collective effects may enable future technologies, e.g., efficient solar cells, low-power transistors, high-density memory

Superconductivity

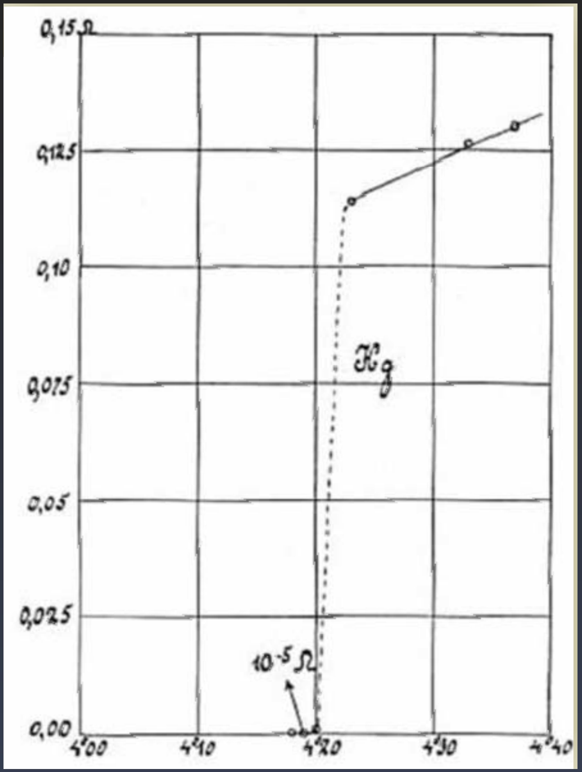
Kamerlingh Onnes, 1911

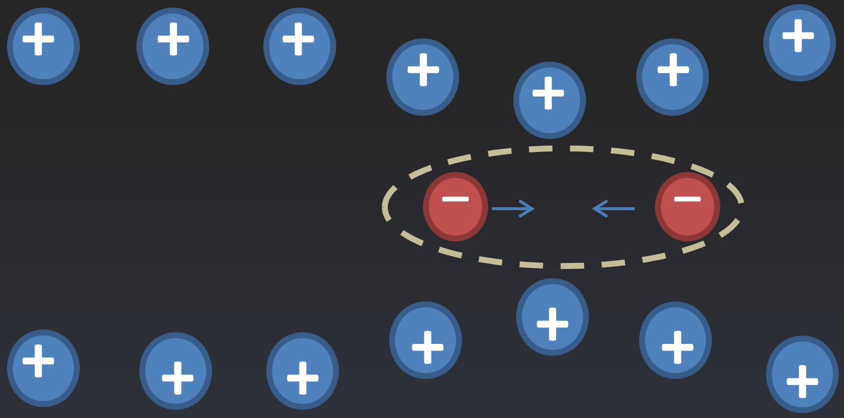




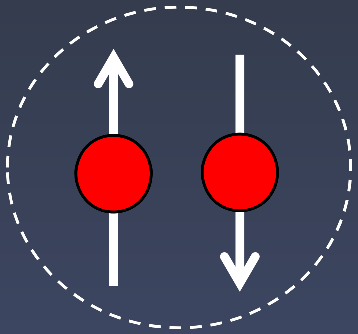


Superconductivity: Collective electronic effect





superconductor: attractive interaction between electrons, no energy lost to lattice



Transport via paired opposite spin electrons, which have same phase: "Cooper pairs" condense into new ground state

→ Collective Effect

$$\Psi(r) = |\Psi(r)| e^{i\varphi(r)}$$

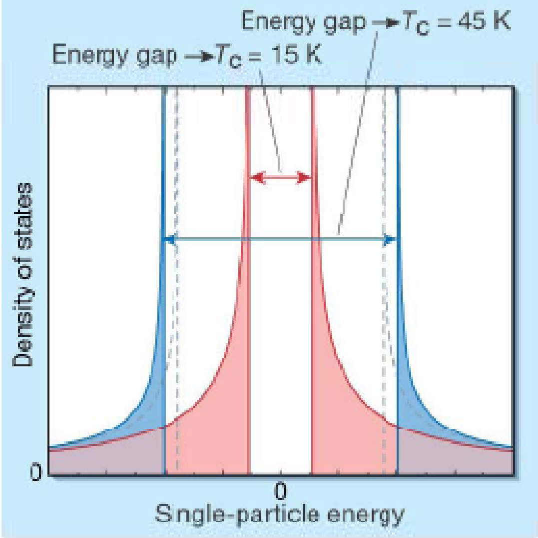
Superconductivity (“Low-Temp”, s-wave)

- electron-phonon interaction leads to an attraction of electrons

- Cooper pairs: bound states of two electrons with opposite momentum and spin (size of Cooper pair: coherence length)

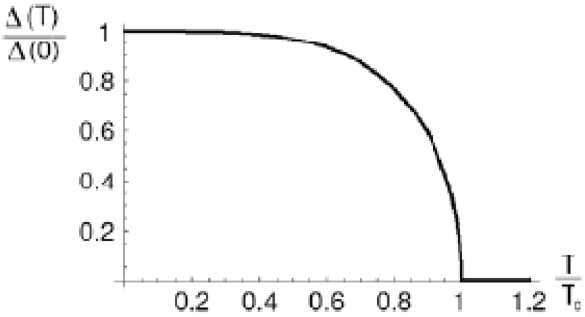
$$\xi_0 = \frac{\hbar v_F}{\pi \Delta}$$

- the net spin is zero and as a consequence they obey Bose-Einstein statistics: at low T all pairs condense in the lowest energy state (no Pauli exclusion !)



- the superconducting state can then be described with a single, macroscopic wave function: $\Psi = |\Psi| \exp(i\phi)$
$|\Psi|^2$: density of Cooper pairs; ϕ: phase of the condensate

- the pairing leads to an energy gap Δ in the spectrum; the density of states is $N_s(E) = N_N(E)\, E/(E^2-D^2)^{1/2}$

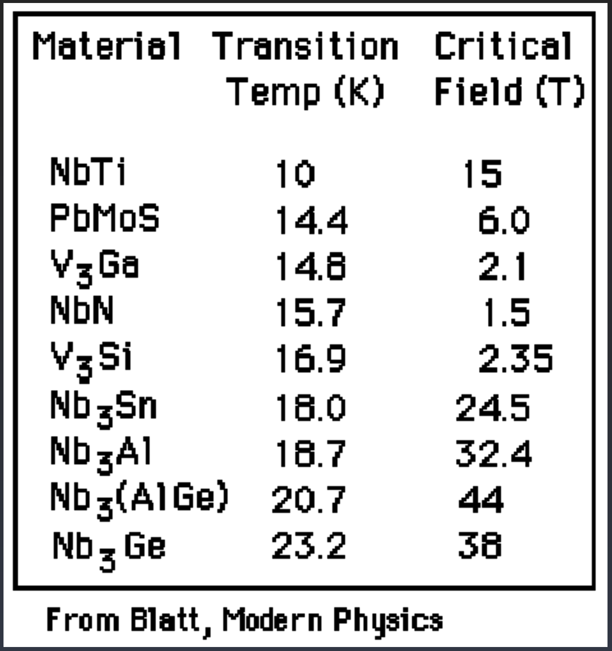


- energy gap $\Delta \approx 1.75 k_B T_C$ needed to excite a quasiparticle from the ground state (condensate)

Many materials are superconducting

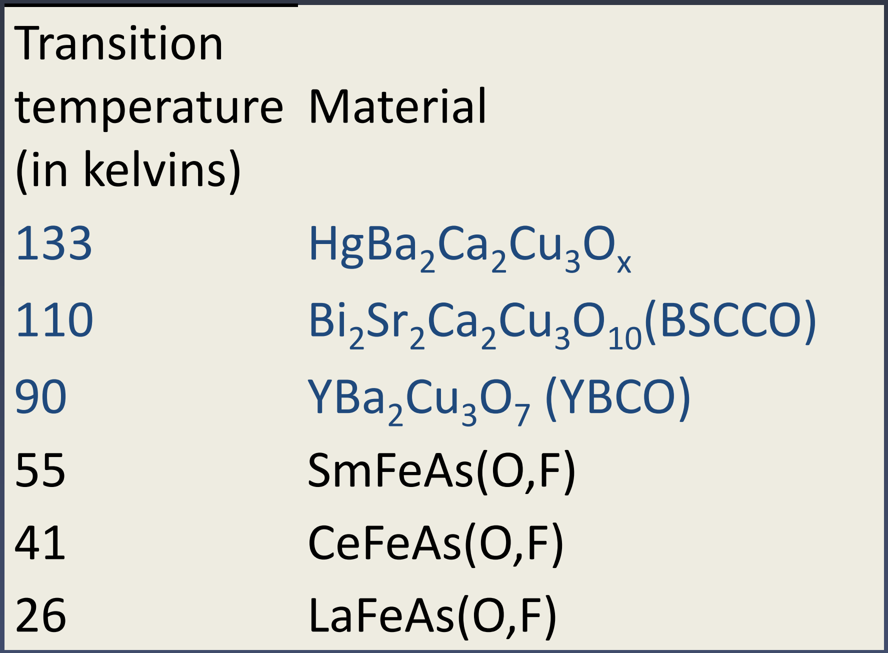
Mat.	Tc
Be	0
Rh	0
W	0.01
Ir	0.1
Lu	0.1
Hf	0.1
Ru	0.5
Os	0.7
Mo	0.92
Zr	0.54
Cd	0.56
U	0.2
Ti	0.39
Zn	0.85
Ga	1.08

Mat.	Tc
Al	1.2
Pa	1.4
Th	1.4
Re	1.4
Tl	2.39
In	3.40
Sn	3.72
Hg	4.15
Ta	4.47
V	5.38
La	6.00
Pb	7.19
Tc	7.77
Nb	9.46



Material	Transition Temp (K)	Critical Field (T)
NbTi	10	15
PbMoS	14.4	6.0
V_3Ga	14.8	2.1
NbN	15.7	1.5
V_3Si	16.9	2.35
Nb_3Sn	18.0	24.5
Nb_3Al	18.7	32.4
$Nb_3(AlGe)$	20.7	44
Nb_3Ge	23.2	38

From Blatt, Modern Physics



Transition temperature (in kelvins)	Material
133	$HgBa_2Ca_2Cu_3O_x$
110	$Bi_2Sr_2Ca_2Cu_3O_{10}$(BSCCO)
90	$YBa_2Cu_3O_7$ (YBCO)
55	SmFeAs(O,F)
41	CeFeAs(O,F)
26	LaFeAs(O,F)

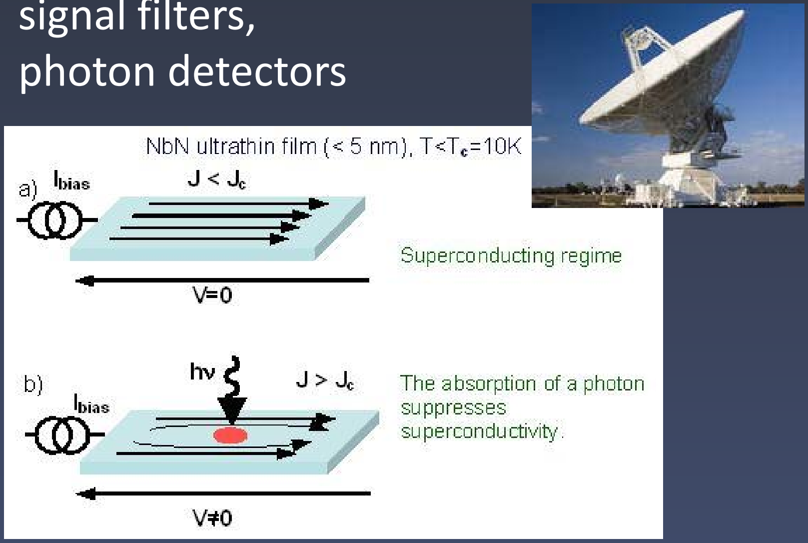
Applications of Superconductivity

Low-volume wires: high-density power use; reduced weight wind turbines

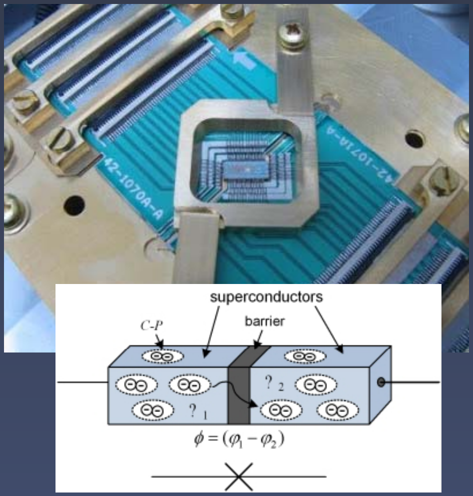
Reduced wire heating: magnets for MRIs, accelerators

Expulsion of magnetic fields: levitating trains, flywheels

Sensitive detectors: signal filters, photon detectors

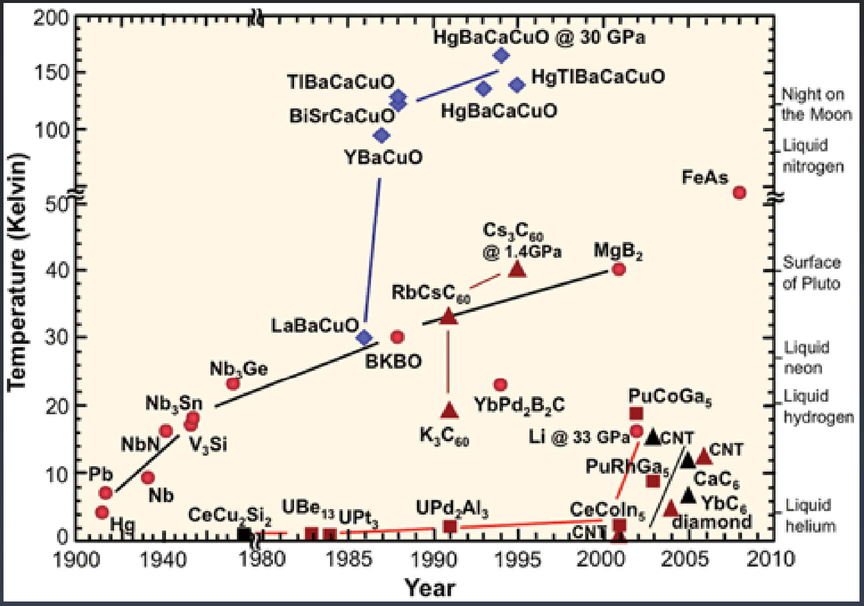


Electronic elements: magnetometers, quantum computing elements

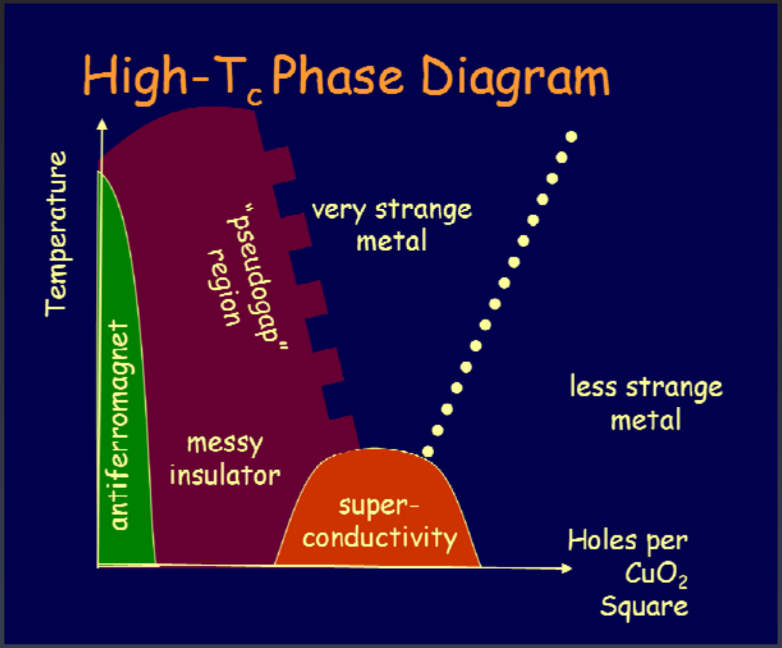


Applications of superconductivity still limited by our lack of understanding …

- Can we increase T_c in high-temperature superconductors?

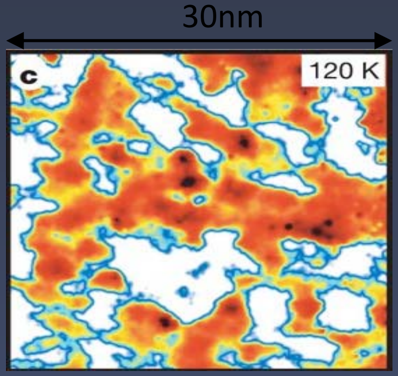


Wikipedia



Reproduced from Cavendish Lab

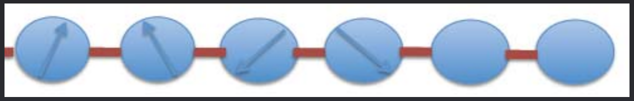
- What is the nature of the pseudogap?
- What is the role of magnetism?
- What other types of collective behavior may be relevant? Charge stripes, spin correlations, phase separation…

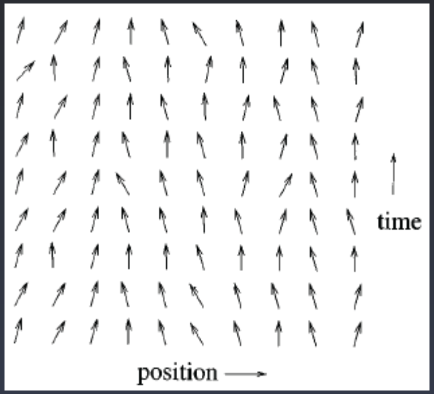


STM above T_c: (Gomes *et al,* Nature, 2007*)*

Applications of superconductivity still limited by our lack of understanding …

- What is the nature of superconductivity in lower dimensions?



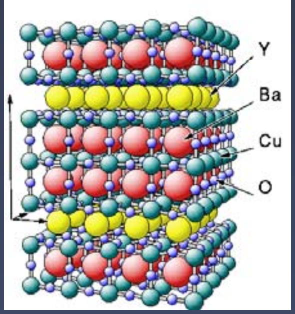


- 1D: Phase fluctuations destroy superconductivity
- 2D: Phase correlations decay as power law

Superconductivity needs: grain size larger than coherence length, limited disorder, limited phase fluctuations …

- Role of disorder?
- Role of phase separation?
- What other types of ground states can exist?

Note: this also relevant to high T_c materials, which are layered, quasi-2D

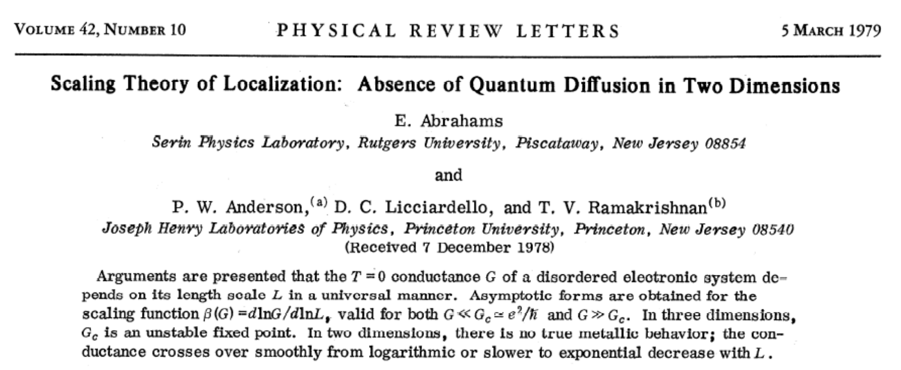


- More specifically, what is the nature of the ground state in a 2D system with superconducting interactions?

Superconducting?
Insulating?
Metallic?

Scaling theory of localization: no metallic states exist below 2D at T=0

→ finite disorder "traps" electron wavefunctions (Anderson localization)



Volume 42, Number 10 PHYSICAL REVIEW LETTERS 5 March 1979

Scaling Theory of Localization: Absence of Quantum Diffusion in Two Dimensions

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and

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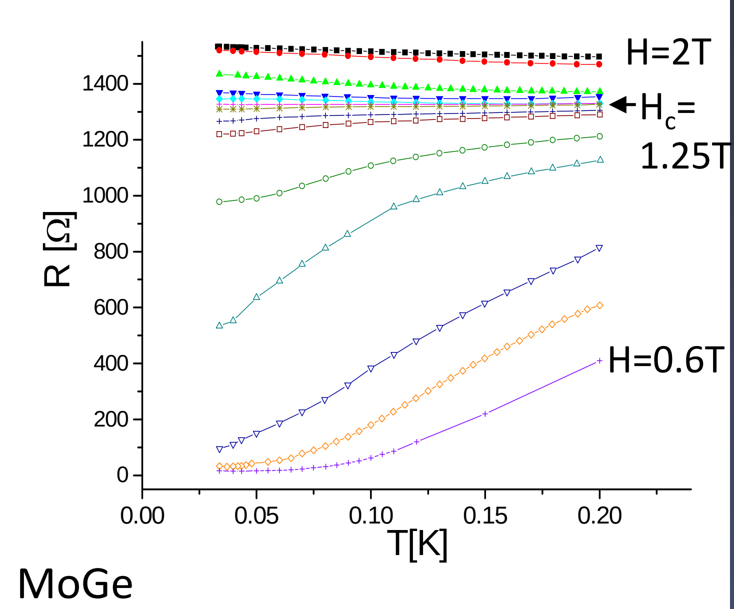
(Received 7 December 1978)

Arguments are presented that the $T=0$ conductance G of a disordered electronic system depends on its length scale L in a universal manner. Asymptotic forms are obtained for the scaling function $\beta(G)=d\ln G/d\ln L$, valid for both $G \ll G_c \simeq e^2/\hbar$ and $G \gg G_c$. In three dimensions, G_c is an unstable fixed point. In two dimensions, there is no true metallic behavior; the conductance crosses over smoothly from logarithmic or slower to exponential decrease with L.

But 2D metallic states have been observed in: superconductors, semiconductor heterostructures …

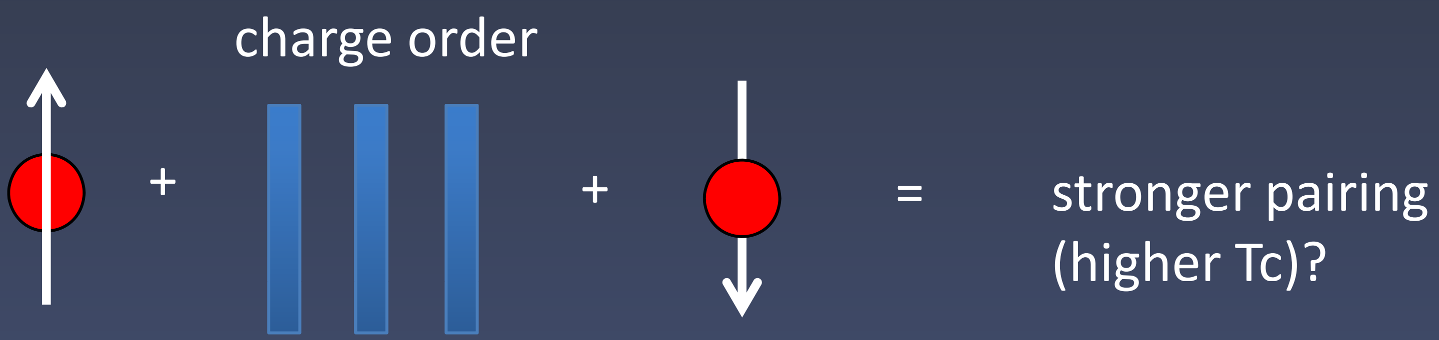


What causes this state and is it related to other anomalous metallic states (e.g., in high T_c materials)?

Issues of superconductors relevant to other collective electronic effects

- Role of: spin-charge ordering, disorder, phase separation, dimensionality
- Nature of phase transition → quantum (T=0) critical point often controls properties
- What other types of ground states can exist?

<u>How do we tackle these questions</u>? We want a way of controlling interactions on a microscopic level, building up to observed effects …



charge order

+ + =

stronger pairing (higher Tc)?

Issues of superconductors relevant to other collective electronic effects

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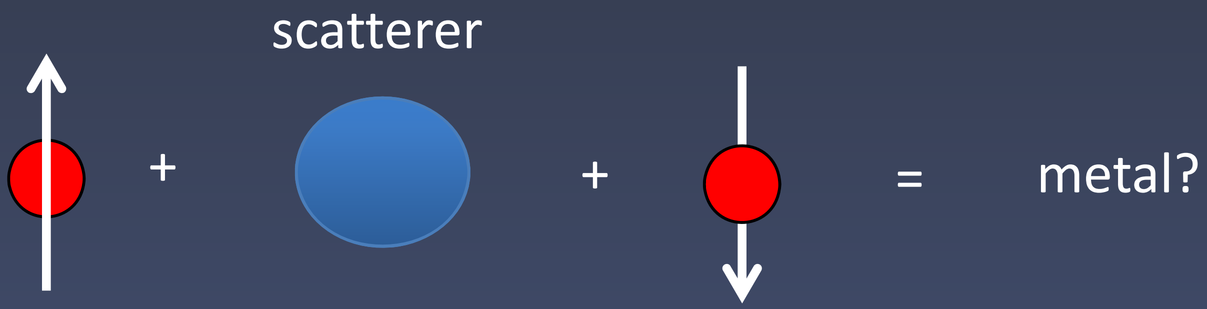

scatterer

\+ \+ = metal?

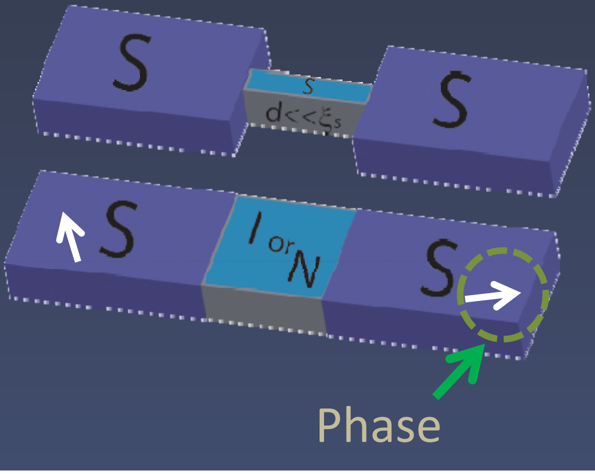
But hard to control individual electrons … What if we instead make interacting superconducting islands?

Superconductivity on each island defined by wavefunction: $\Psi(r) = |\Psi(r)| e^{i\varphi(r)}$

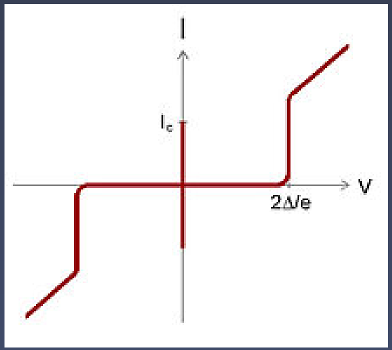
Interacting, or *coupled*, islands can have the same phase: $\varphi_1 = \varphi_2$ and pairs can flow between islands

When islands are *not* well-coupled, $\varphi_1 \neq \varphi_2$, and no supercurrent flows

This is the well-known Josephson Junction

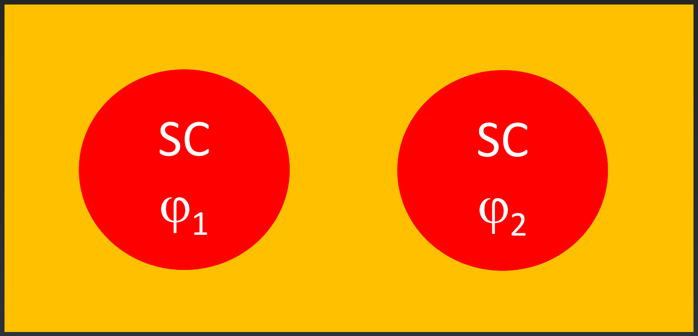


$$I_{SC} = I_C \sin(\Delta\varphi)$$



So we can control superconductivity in system of islands by controlling their coupling.

How do we do that? Via the substrate
(or any "weak link")



metallic substrate:

Island coupling ~ e^{-d/ξ_N}

d = island spacing

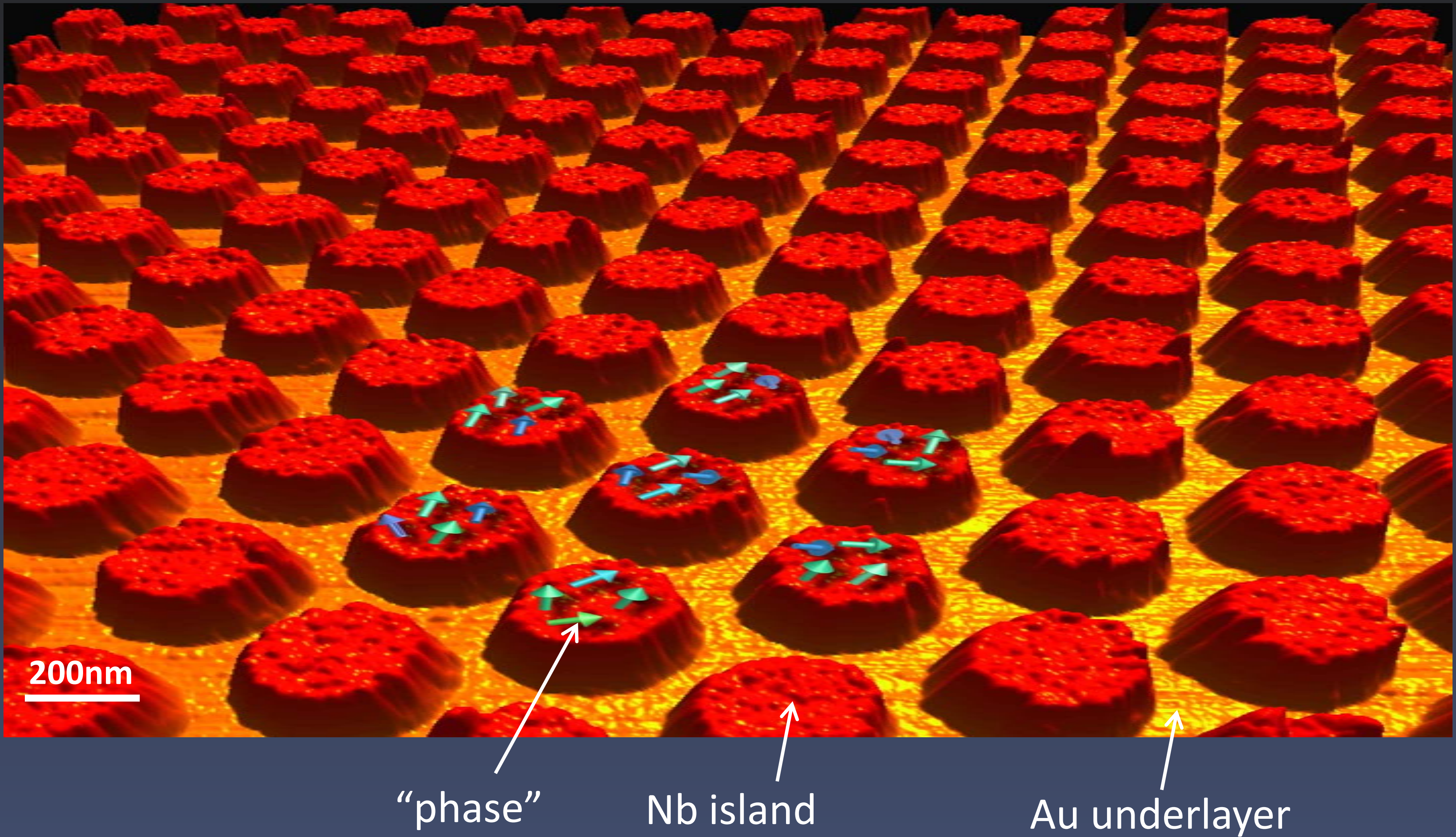
ξ_N = coherence length of normal metal

$$\xi_N = \sqrt{\frac{\hbar D_N}{k_B T}}$$

- Of course, properties of superconducting island also matter: e.g., if islands are small or are composed of grains, phase fluctuations can occur on each island

Coupling many interacting superconducting islands

→ Control interactions, look at macroscopic phenomena that emerge



Coupling many interacting superconducting islands

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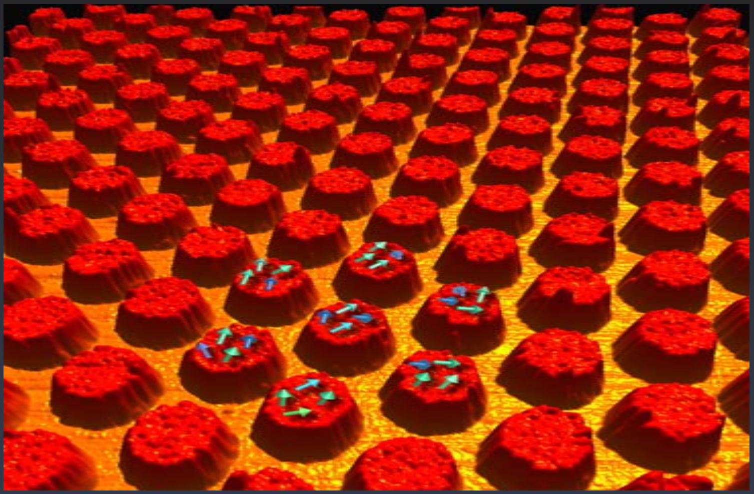


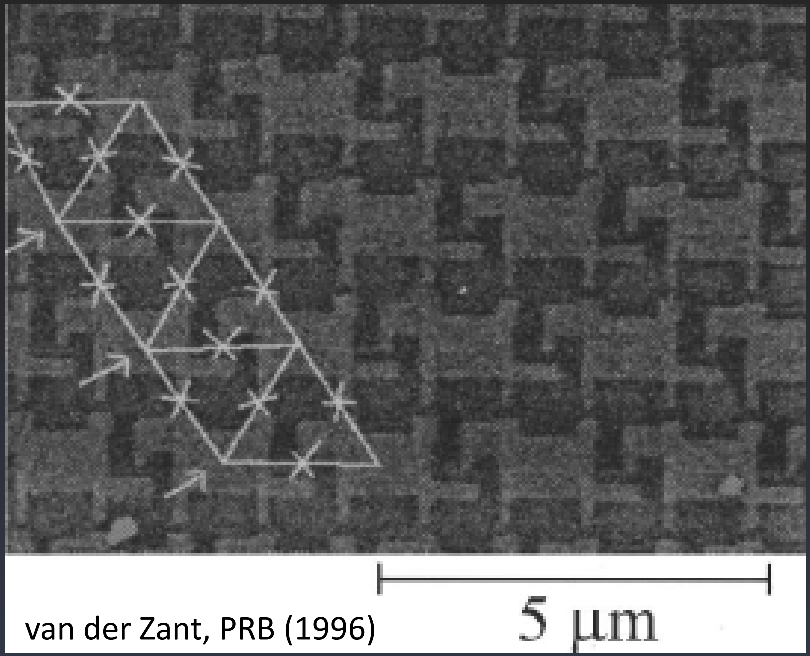
- Arrays of > 10,000 islands
- Control of superconductor and substrate materials
- **Full control of each island’s size & position**
- 2D superconductor

Approach key questions related to superconductivity and collective phenomena:

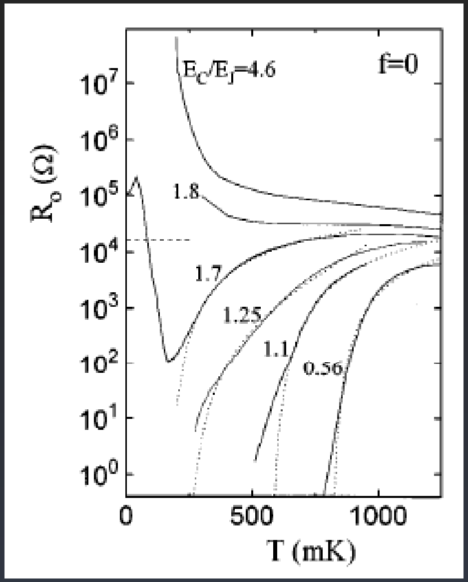
- Effect of disorder
- Phase separation (intermediate metal)
- 2D ground states
- Different ranges of superconducting coupling

Josephson junction arrays have a long history

Al/AlOx/Al junctions



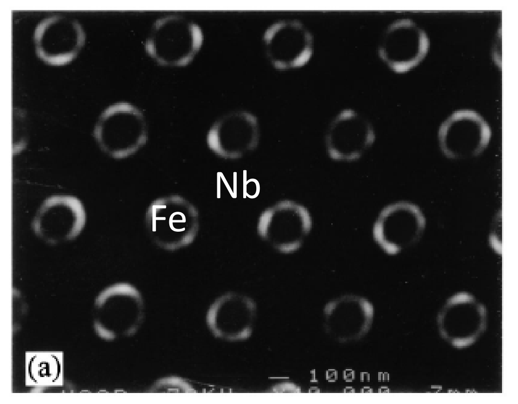
van der Zant, PRB (1996)

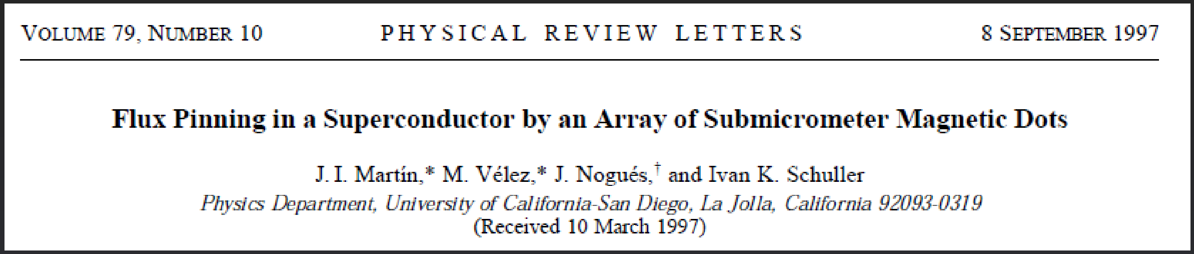


What's New?

- → Fabrication capabilities (electron beam lithography – individual control of island placement)
- → Mesoscopic islands (< 300 nm)
- → Focus on island spacing, 2D metallic states, new substrates, disorder …

Island arrays also have an illustrious history

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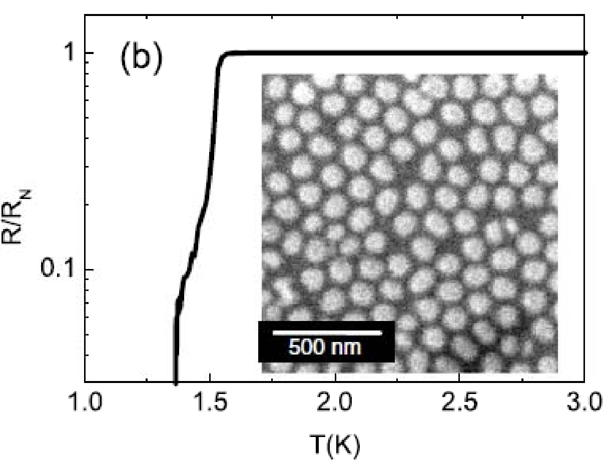
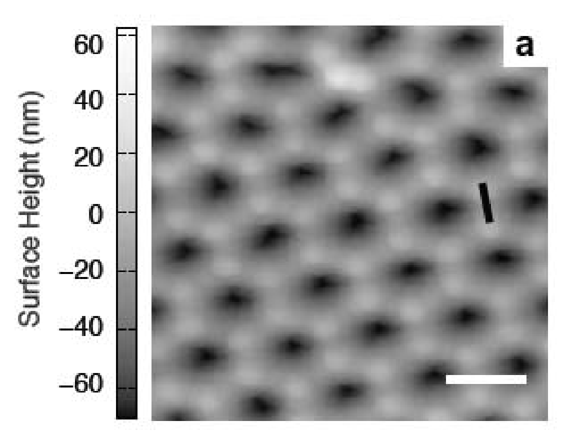
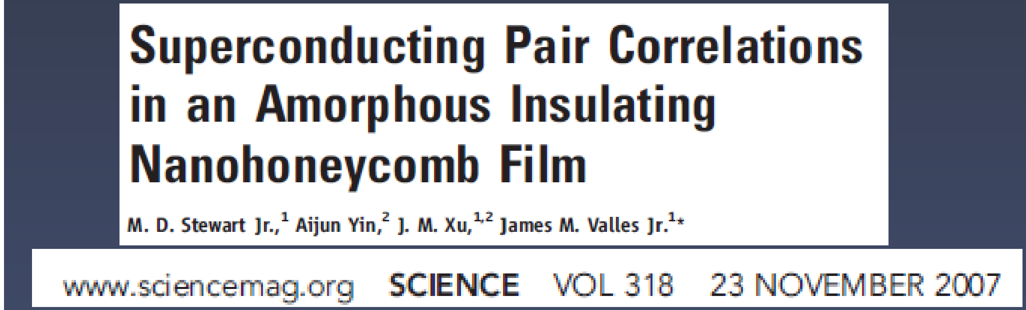
Flux Pinning in a Superconductor by an Array of Submicrometer Magnetic Dots

J. I. Martín,* M. Vélez,* J. Nogués,† and Ivan K. Schuller
Physics Department, University of California-San Diego, La Jolla, California 92093-0319
(Received 10 March 1997)

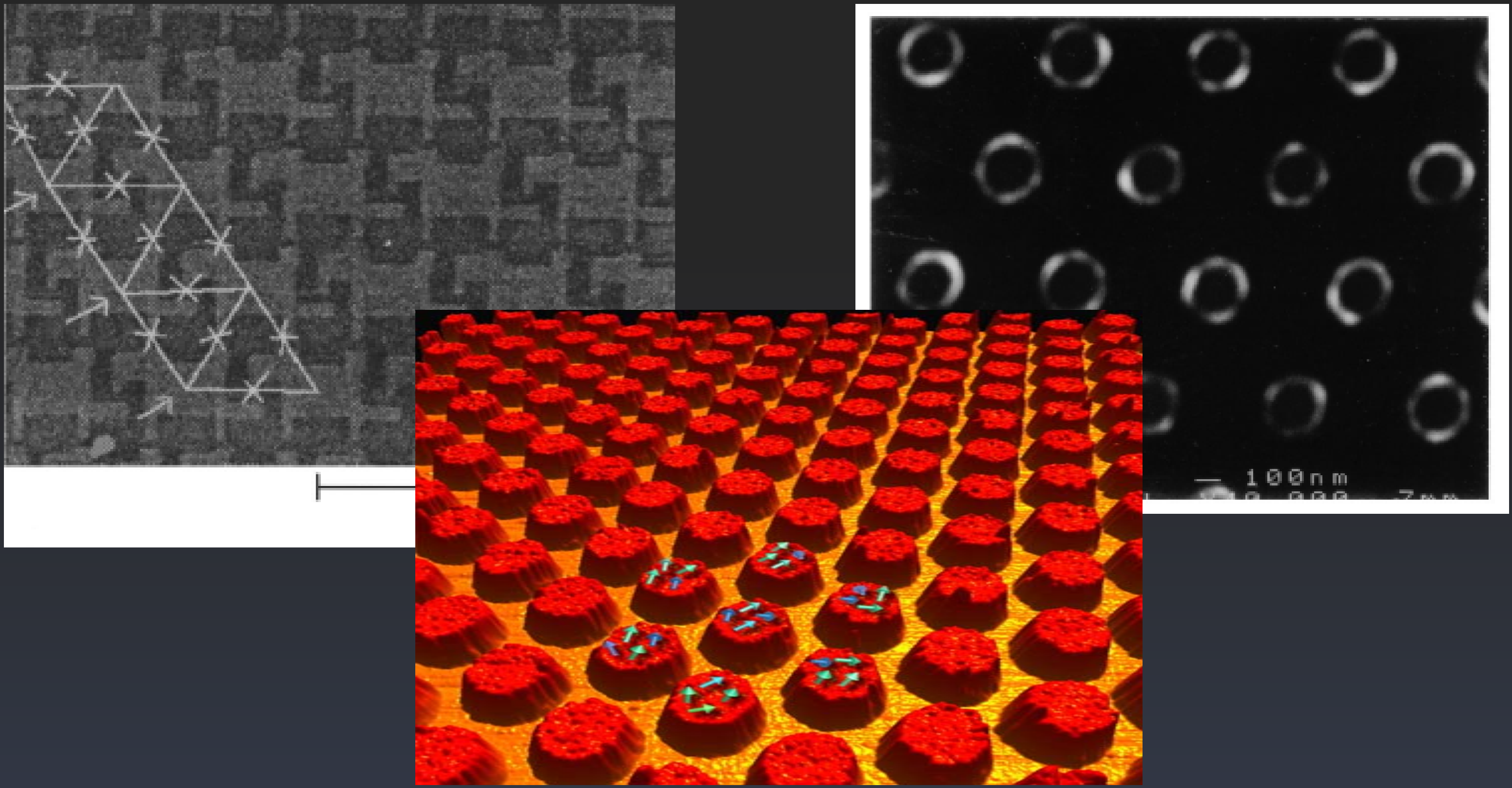





Superconducting Pair Correlations in an Amorphous Insulating Nanohoneycomb Film

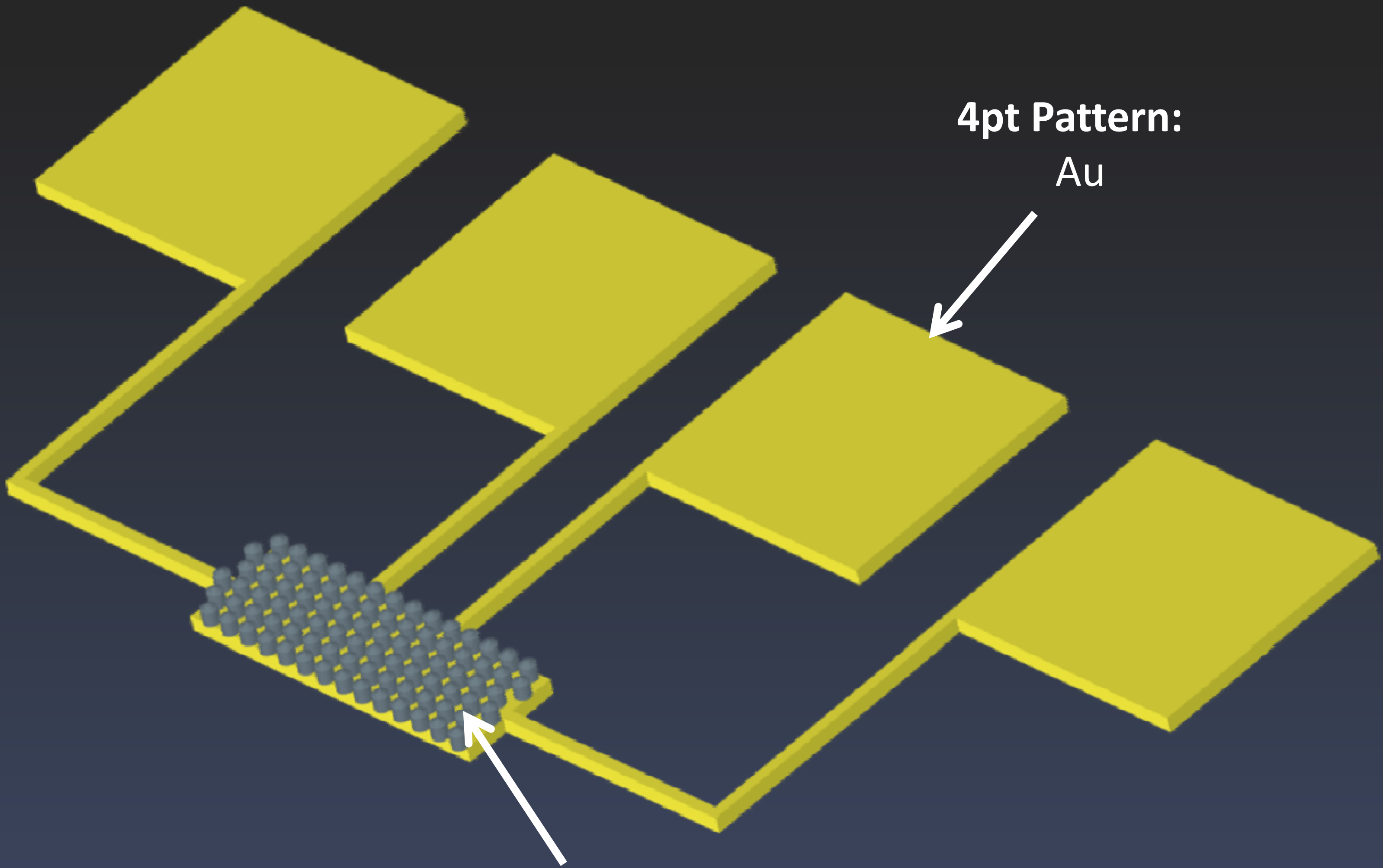
M. D. Stewart Jr.,[1] Aijun Yin,[2] J. M. Xu,[1,2] James M. Valles Jr.[1]*

www.sciencemag.org SCIENCE VOL 318 23 NOVEMBER 2007



“ We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time”
-T.S. Eliot, Four Quartets

Fabrication of superconducting island arrays



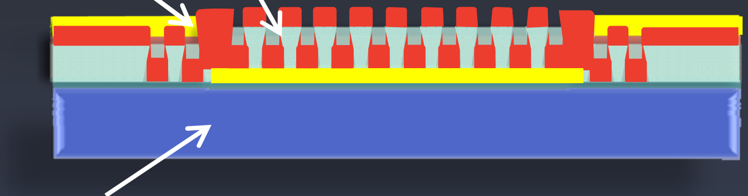
4pt Pattern:
Au

Superconducting
Nb islands

Fabrication of superconducting island arrays

Electron Beam Lithography / E-Beam Evaporation of Nb / Photolithography of Au

(mill surface in-situ for clean interface)

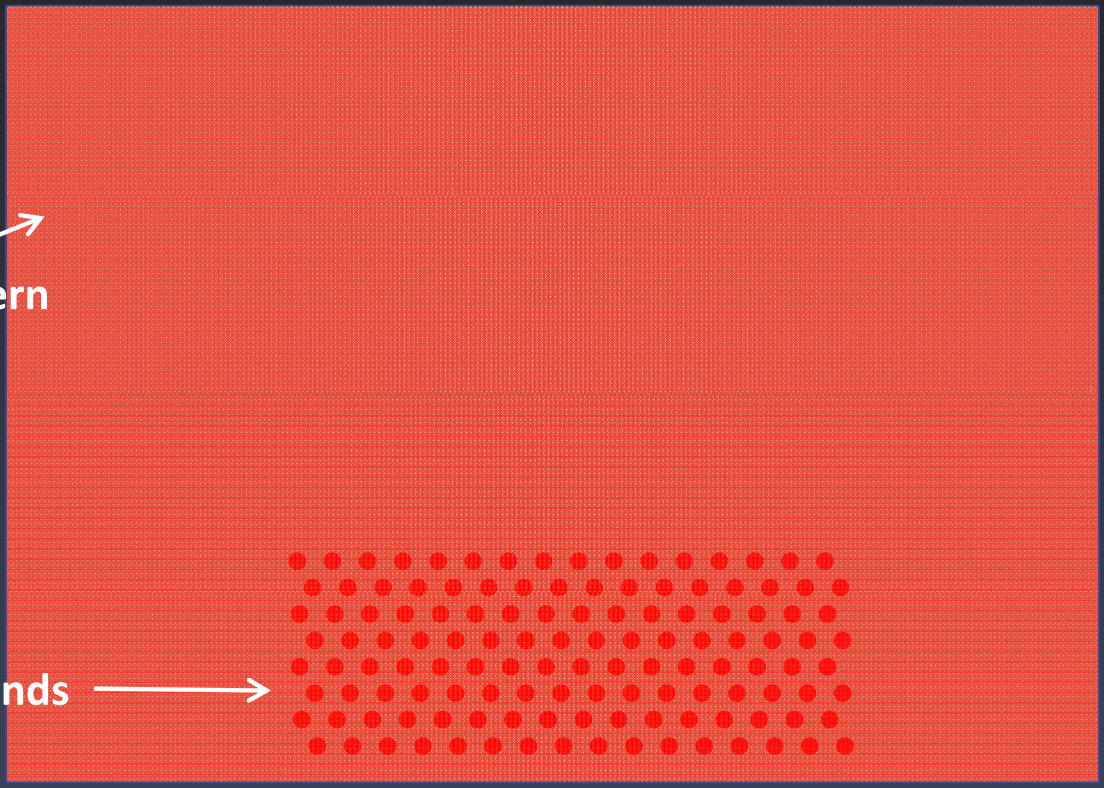


PMMA (e-beam sensitive resist)

Photoresist

Nb

SiO$_2$ substrate



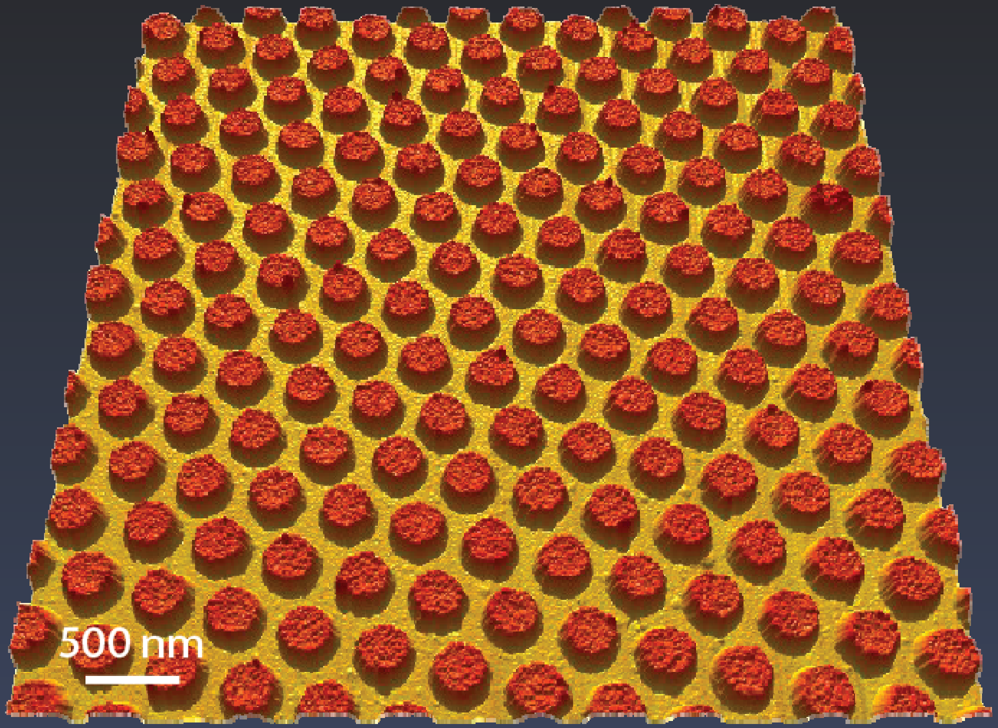
Au 4 pt pattern

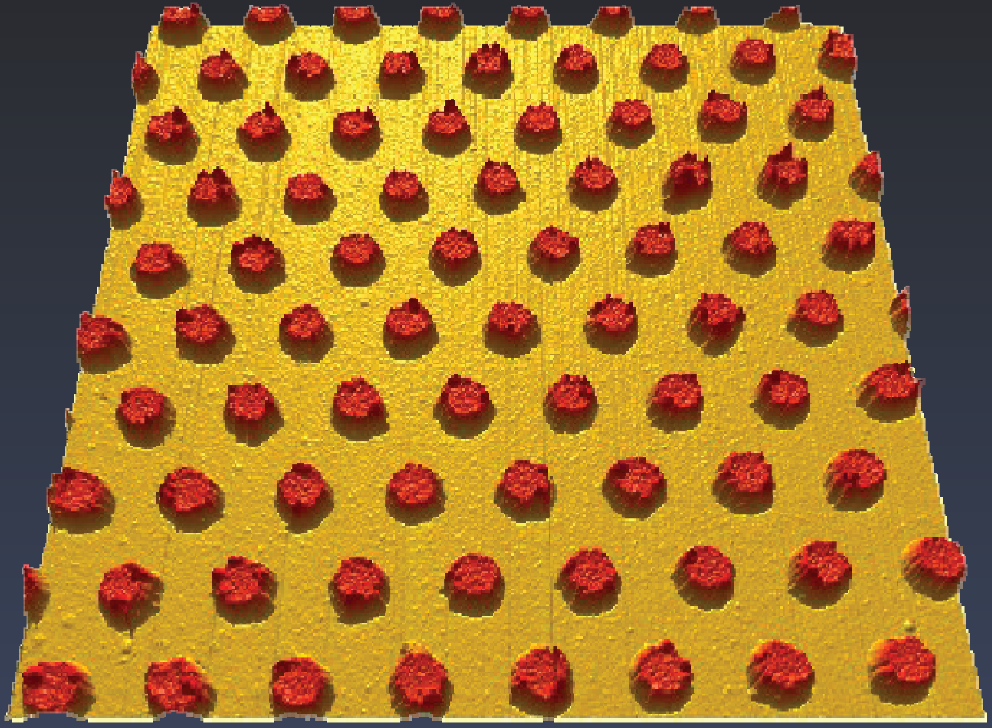
Nb islands

Side View

Top down View

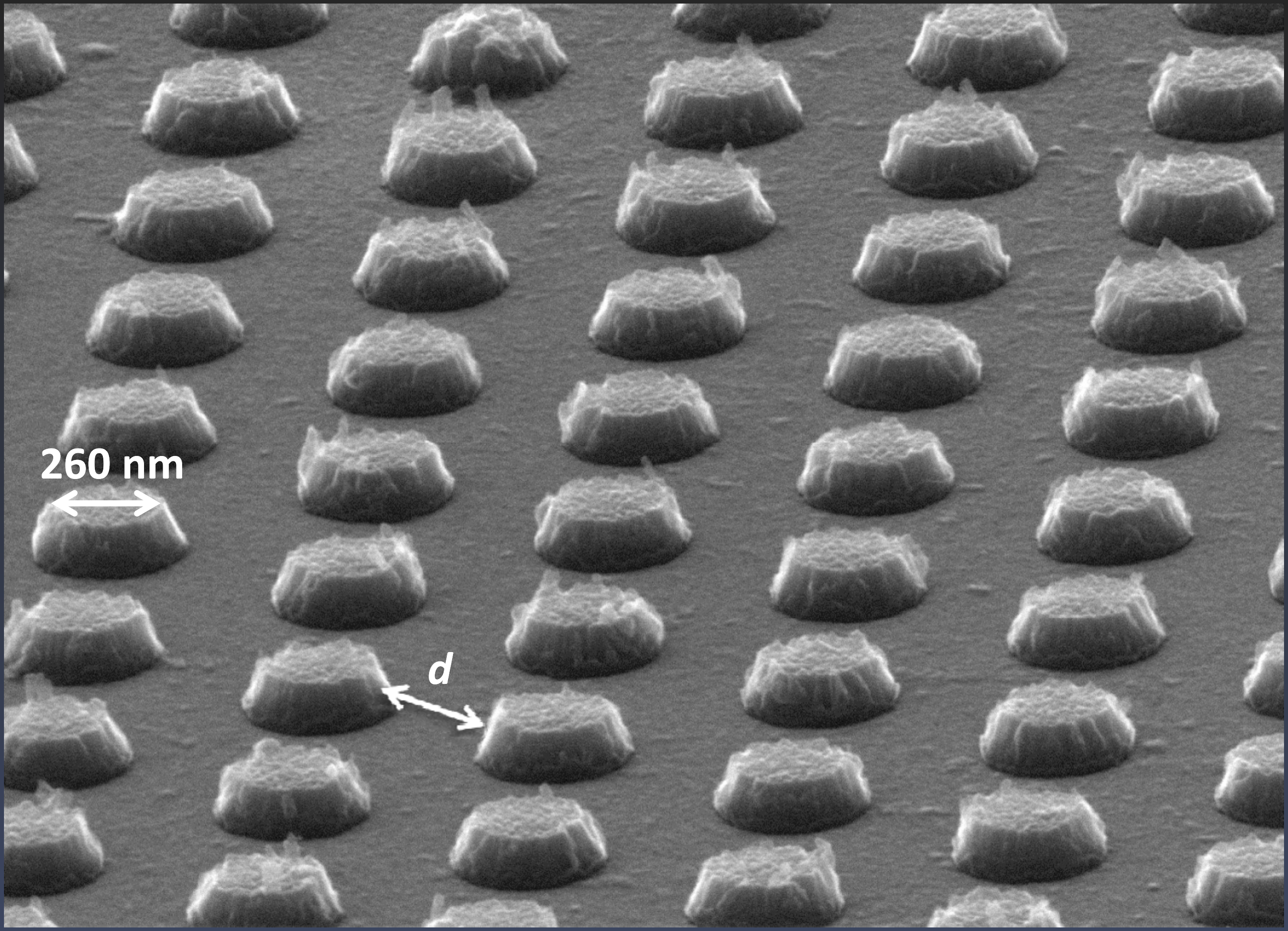
Island Arrays (AFM image)


140 nm spaced islands


340 nm spaced islands

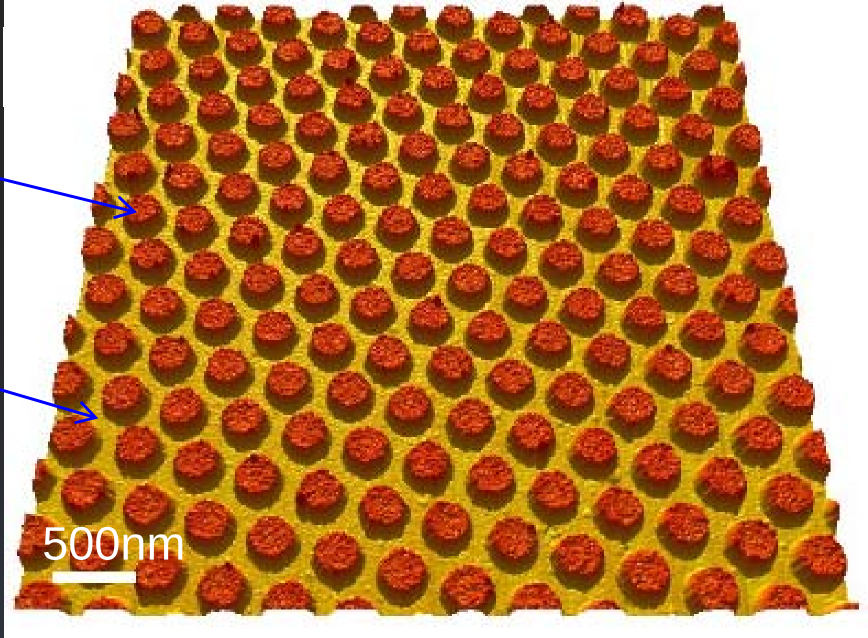
Each substrate contains 6 different arrays, each identical except for island spacing

SEM of islands



Note columnar grains evident in each island

Device Configuration



Superconductor: Nb (90 & 150 nm thick)

Normal Metal: Au (10 nm thick)

Island Diameter: 260 nm

$\rho_{Nb}(10\text{ K}) \approx 1.12\times10^{-5}\ \Omega\cdot\text{cm}$

$\rho_{Au}(10\text{ K}) \approx (6.25\pm0.75)\times10^{-6}\ \Omega\cdot\text{cm}$

mfp $l = 2/(\rho v_F^2 e^2) \rightarrow l_{Nb} \sim 8\text{nm},\ l_{Au} \sim 14\text{nm}$

$$\xi_{SC}^{Nb}(T_c \approx 9.1\text{ K}) \approx 27\text{ nm}$$

$$\xi_N = \sqrt{\hbar D/(k_B T)} \approx 210\text{nm}/\sqrt{T}$$

*Island diameter >> ξ_{SC}
*Island spacing > ξ_N
(e.g., for T>5K, ξ_N < 90nm)

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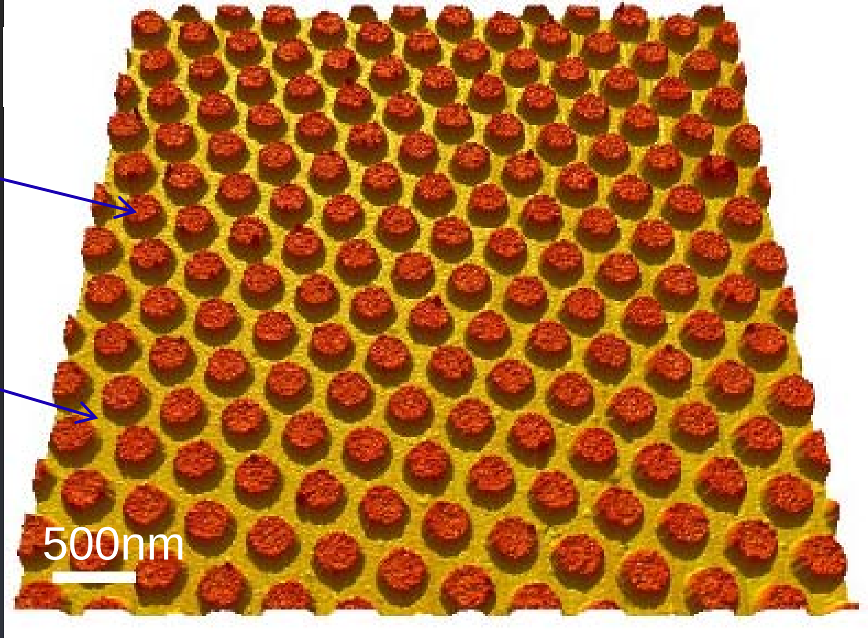

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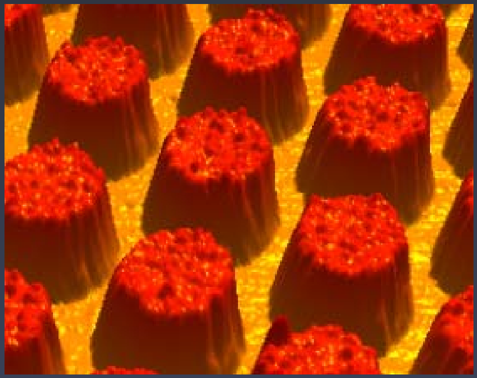
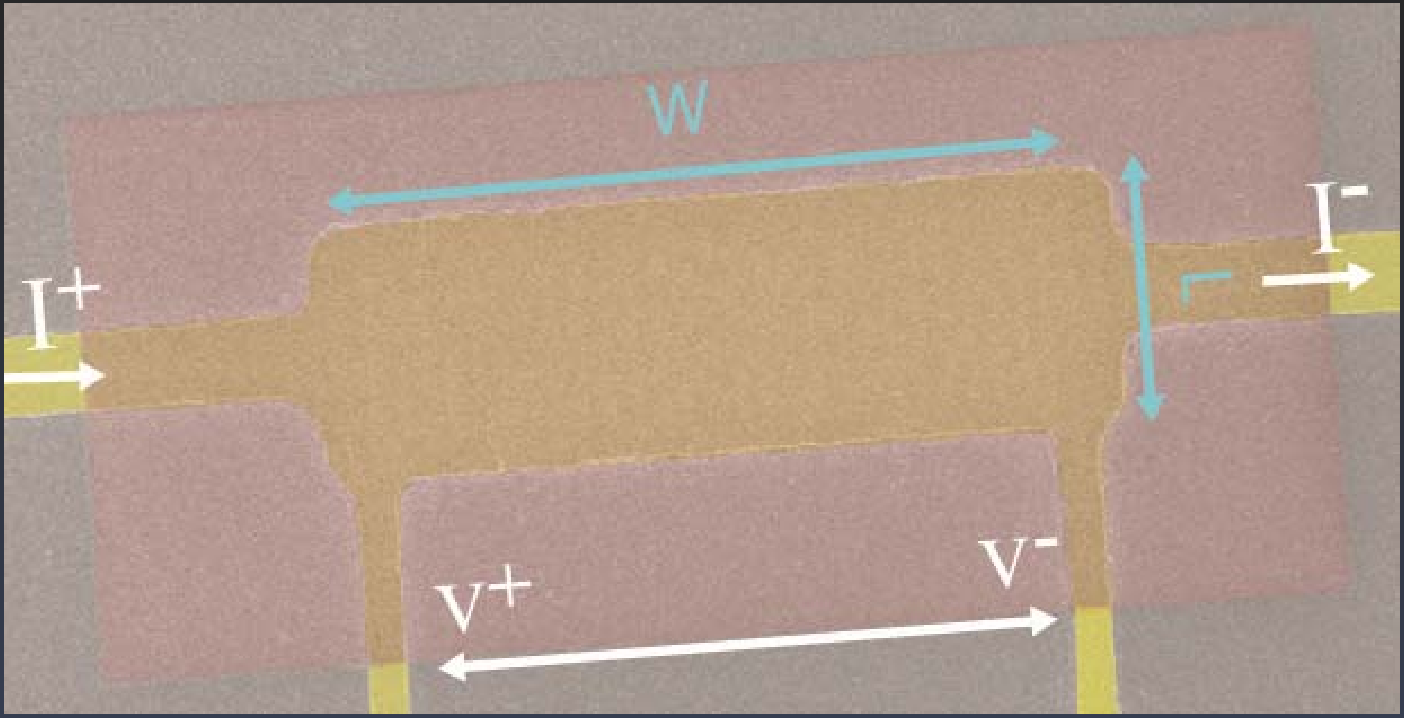


Note: Nb is granular.
Grain size ~ 30nm
(similar to ξ_{SC})

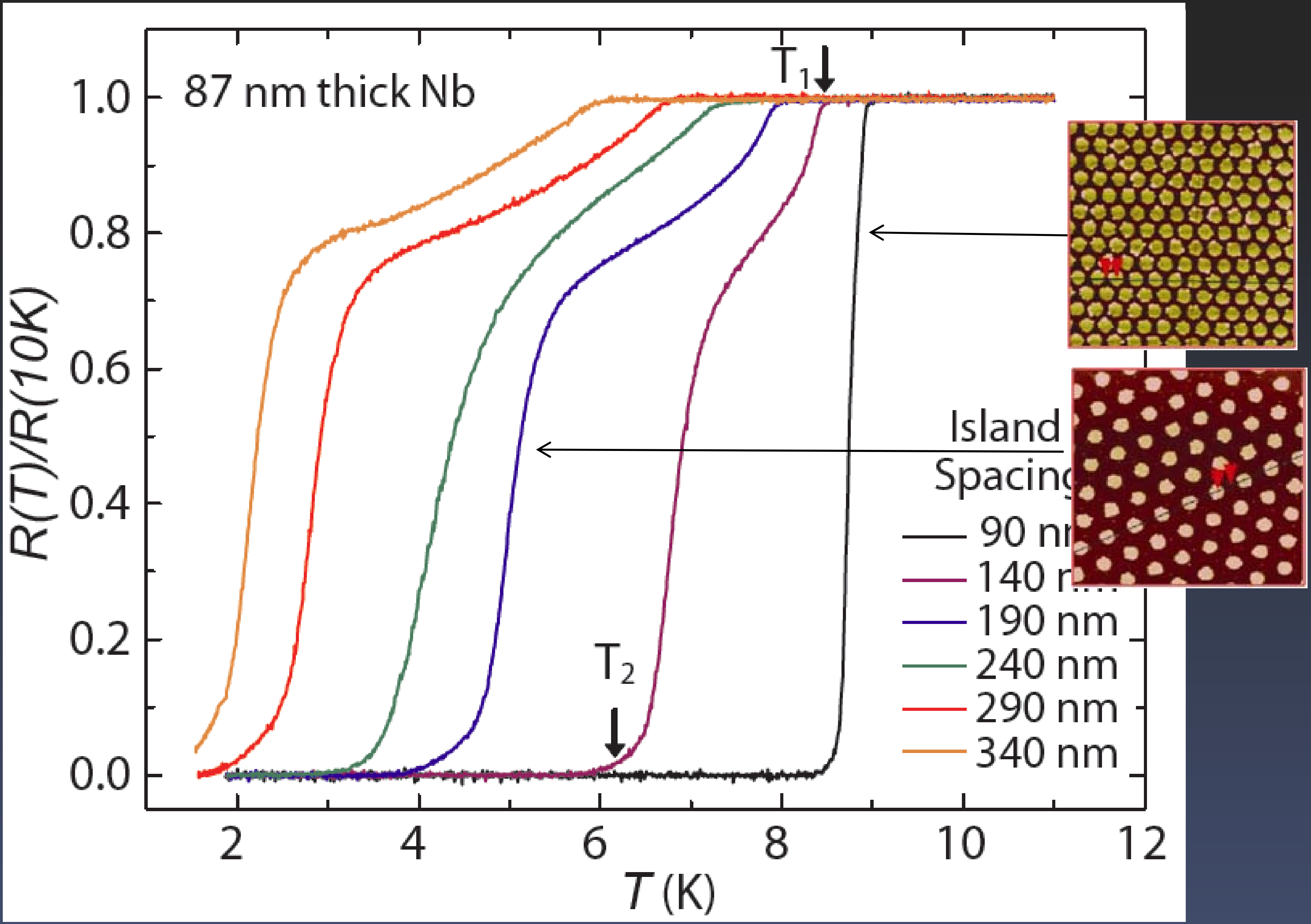
Determined via SEM, XRD. Prev. seen for evaporated Nb: e.g., Asada & Nose, *Jour. Phys. Soc. Japan* **26**, 347

Measurement configuration



Pumped He-4 Cryostat	T = 1.6 K – RT
He-3 Refrigerator	T = 245 mK – 1.8 K, B = 0 – 8 T
He-3/He-4 Dilution Refrigerator	T = 15 mK – 1.2 K, B = 0 – 10 T

Resistance vs. temperature for various island spacing



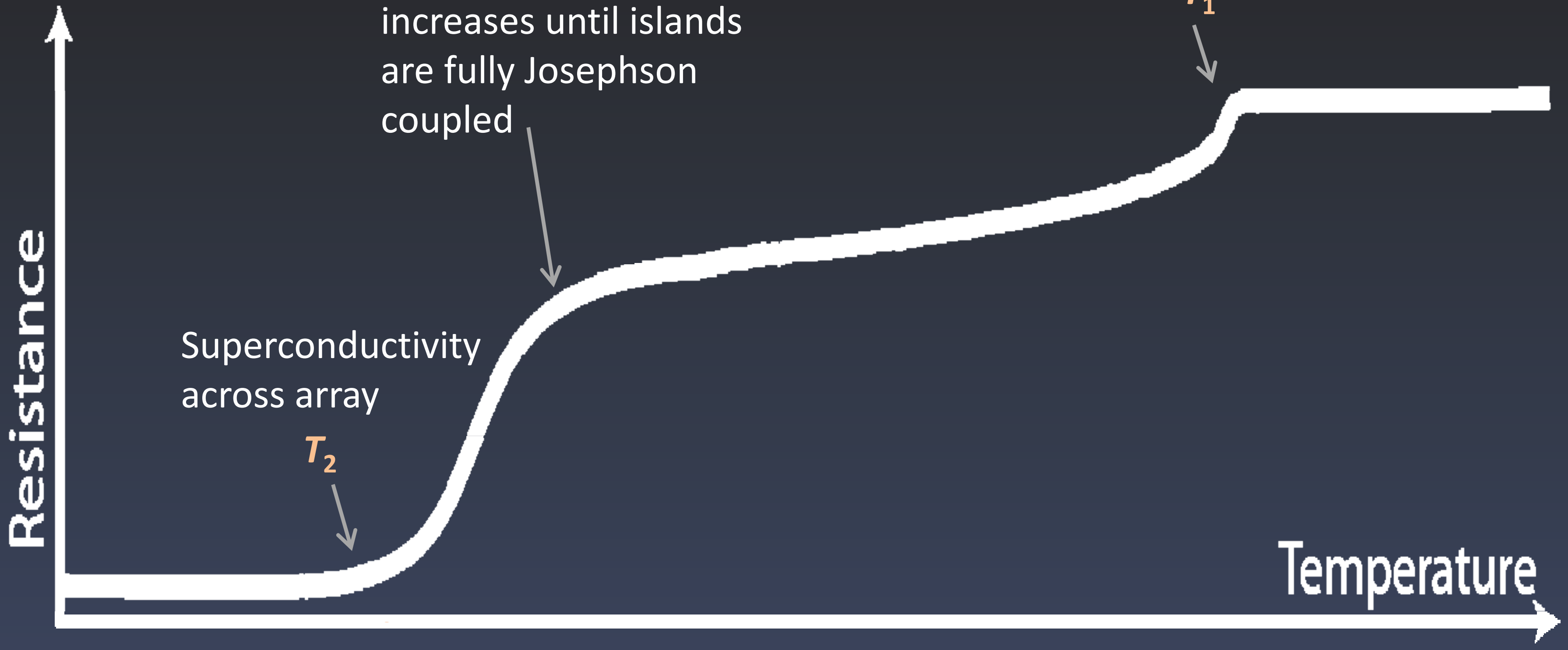
Two-step transition to superconductivity

$$\xi_{Au}(T) = \sqrt{\frac{\hbar D_N}{k_B T}} \approx \frac{268}{\sqrt{T}}\, nm$$

increases until islands are fully Josephson coupled

Individual Nb islands become superconducting

T_1

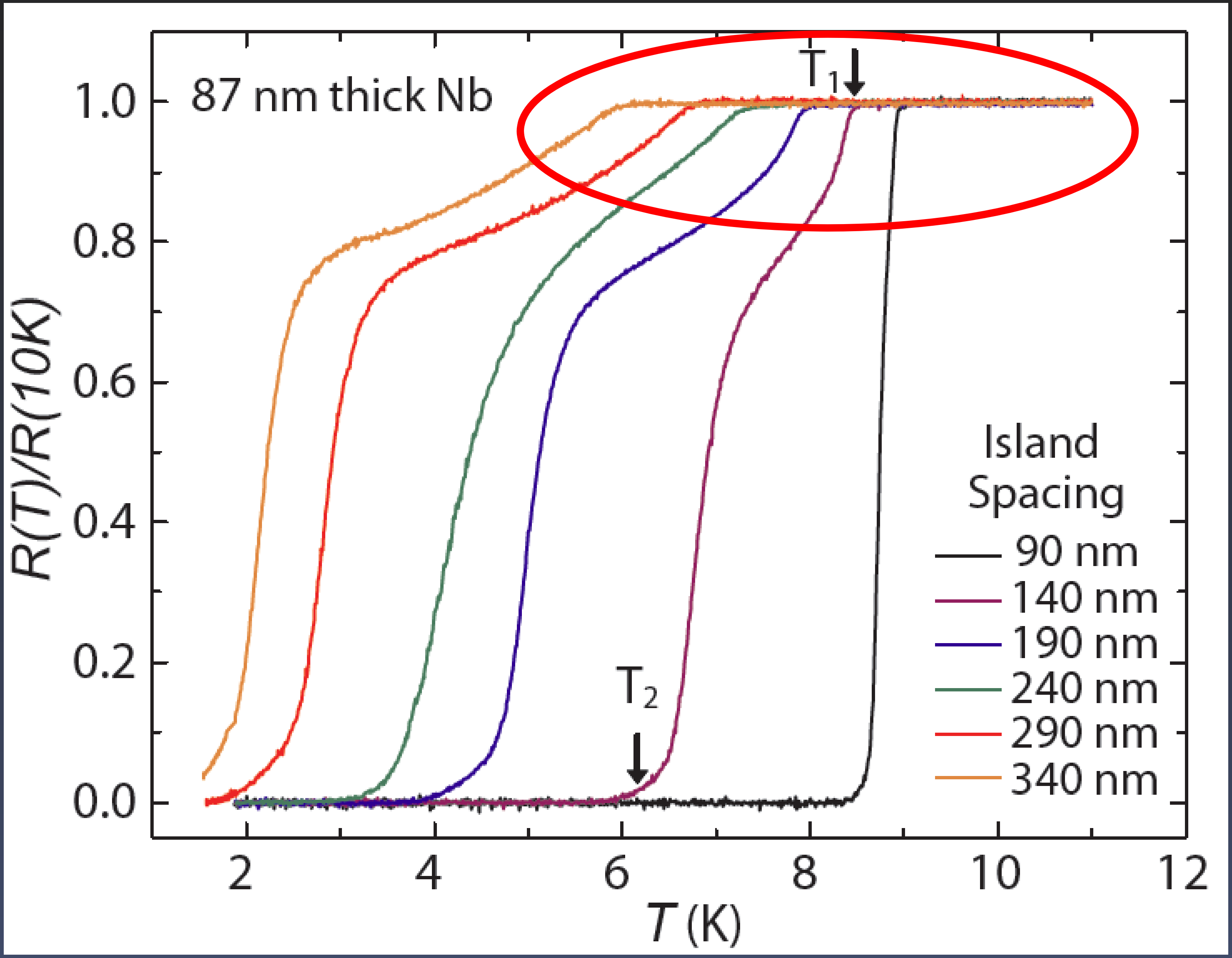


Superconductivity across array

T_2

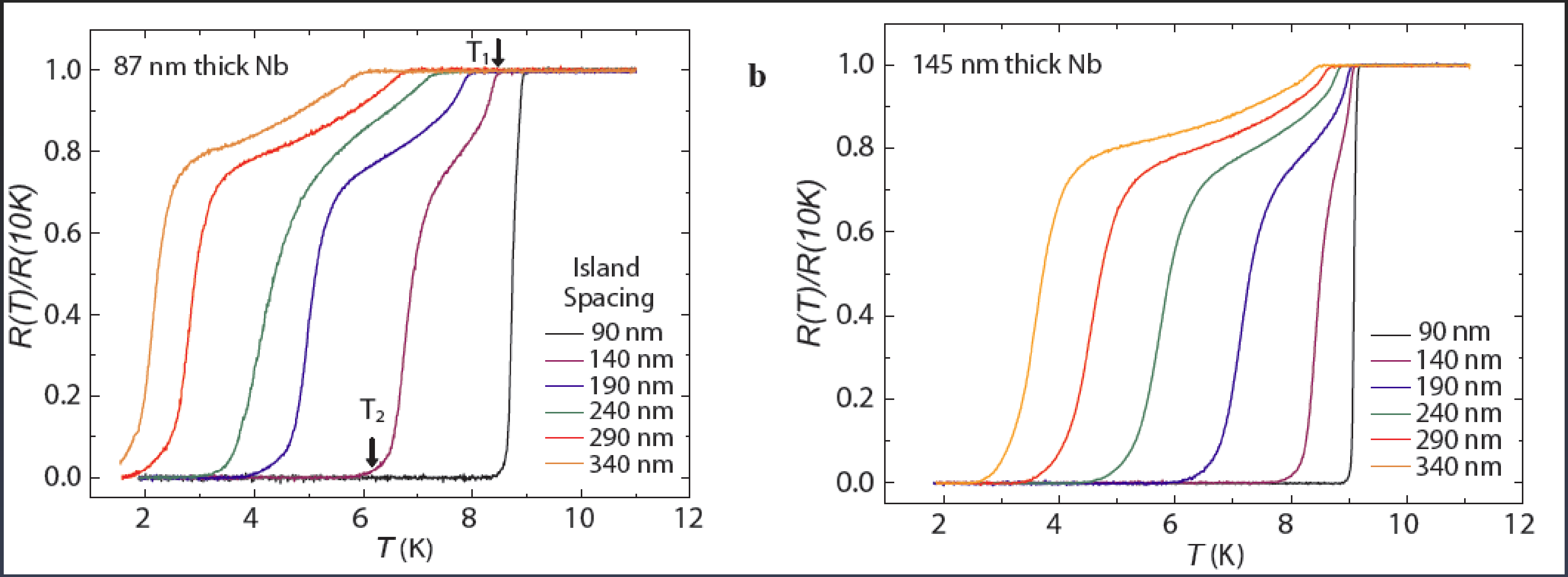
T_1 is the island transition:

Why does T_1 depend on island spacing?



Nature Physics ***8***, *59 (2012)*

Resistance vs. temperature for various island spacings & two Nb thicknesses

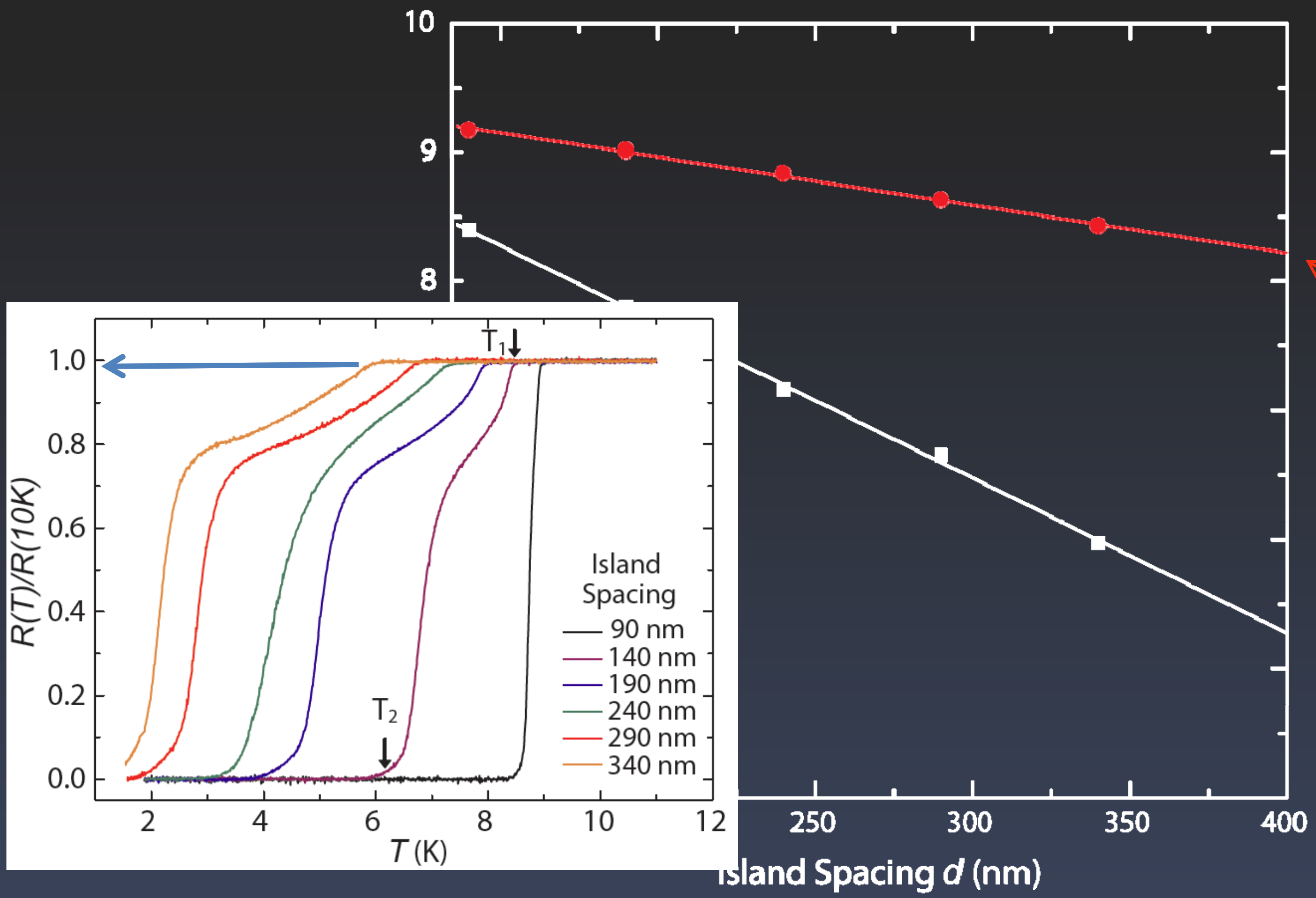


Island diameter is ~ 10 times ξ_{Nb}

Transition temperatures higher in taller islands

Both transitions suppressed with increasing island spacing

T_1 Suppressed Linearly with Island Spacing



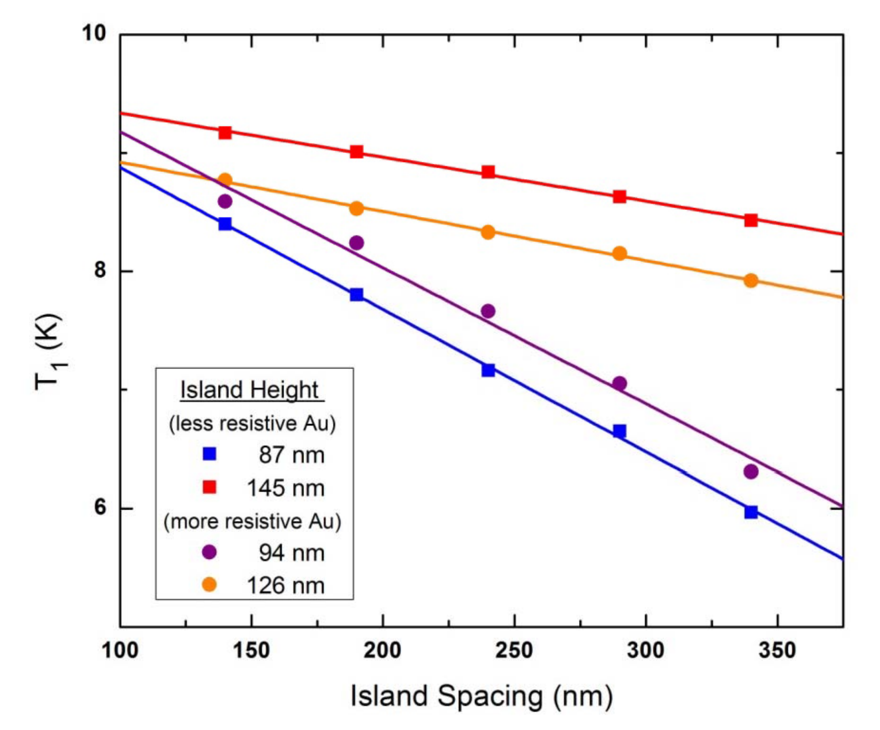
Extrapolates to T=0 at:

2600 nm

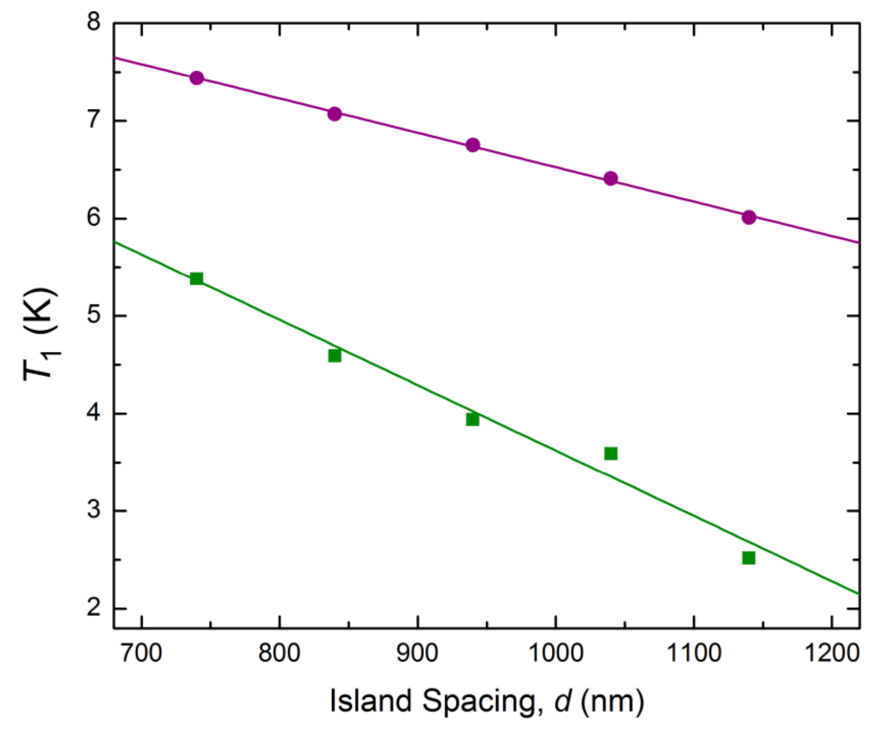
840 nm

T_1 extrapolates to zero at finite island spacing
→ Zero-temperature metallic state in 2D

T_1 Linear Suppression occurs for all samples:



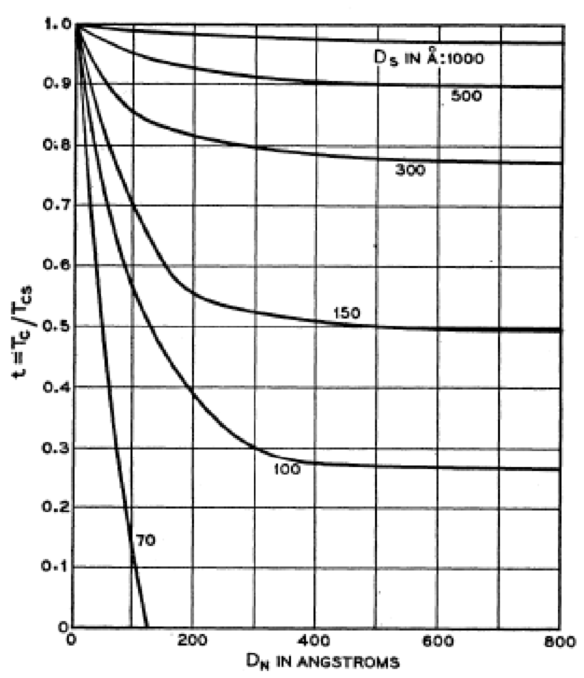
More resistive gold substrate



Larger island spacing

T_1 not suppressed just by presence of normal metal …

T_c can be depressed in normal metal-superconductor bilayers



Pb/Cu bilayer


[a] P. Hilsch, Z. Physik 167, 511 (1962)

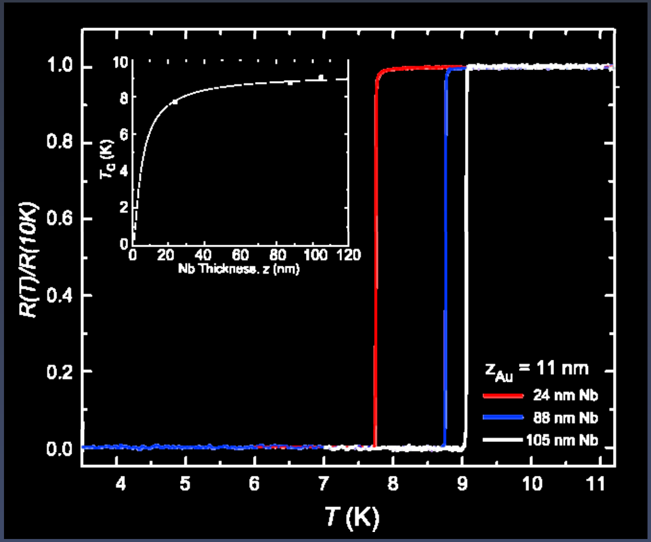
(see Werthamer, Physical Review, 1963)

We are not in this regime!

-For island thickness > ξ_S (~ 30nm) expect same T_1 for d > ξ_N (210nm/√T), i.e., for all curves

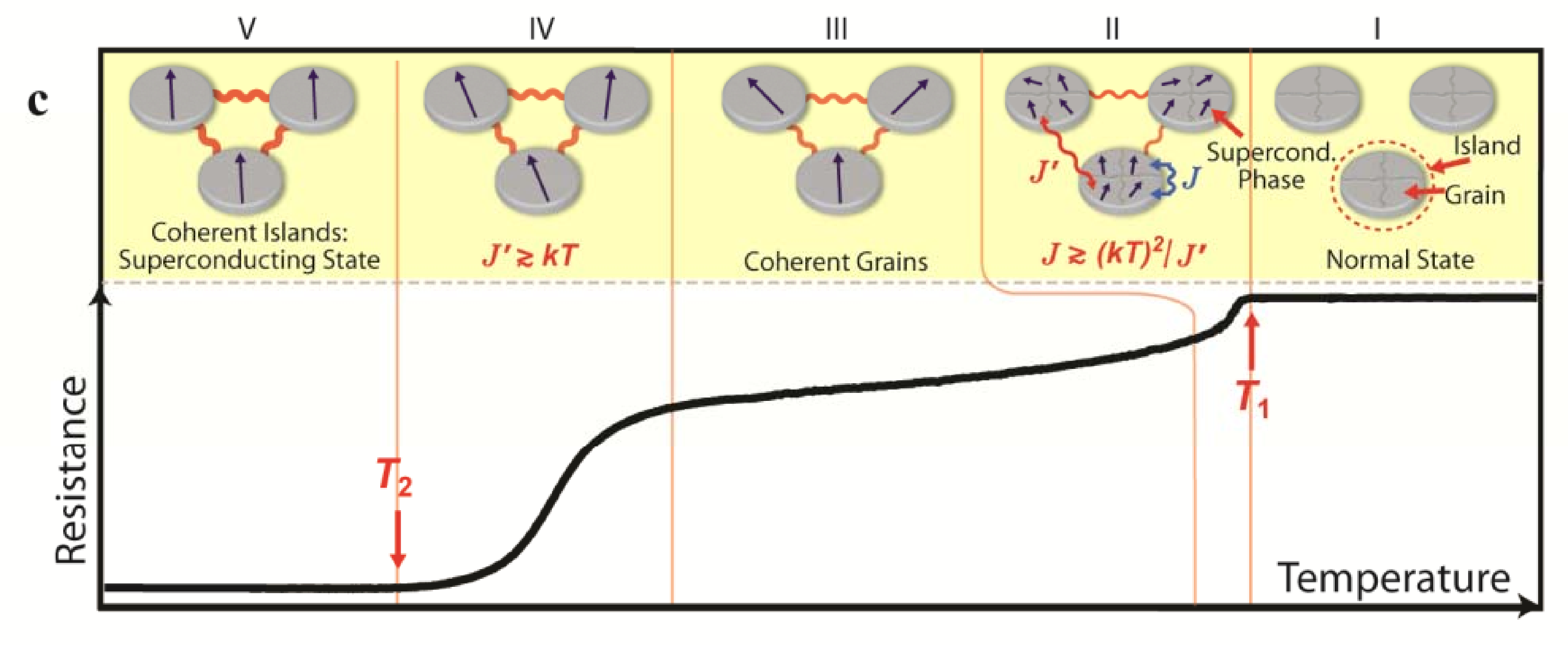
-Would expect T_c of d=90nm to be strongly depressed from bulk, but $T_{d=90}$=9.0K

-Some thinner islands do not show stronger depressions



So what is causing approach to metallic state?

T_1 behavior: phase fluctuations of **grains** on islands

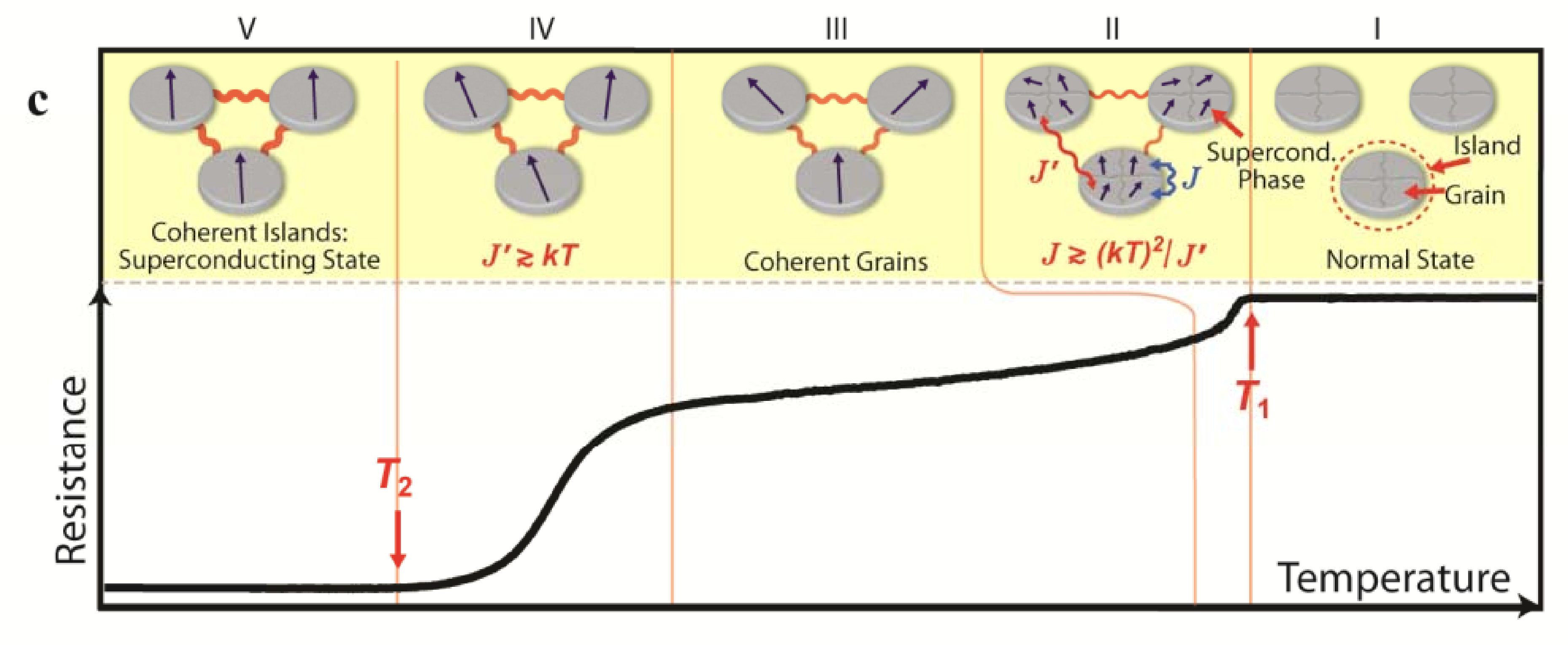


Islands have 30nm grains → Phase on these grains fluctuates and prevents superconductivity

Weak coupling to neighboring islands damps phase fluctuations, enables superconductivity on individual islands

*see Nature Physics **8**, 59 (2012)*

T_1 behavior: phase fluctuations of **grains** on islands



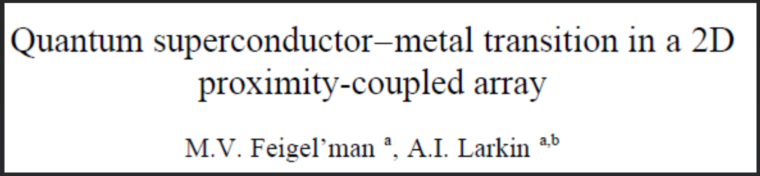
→ There exists a stabilized regime of “regional” correlations between islands (i.e., not local, not global)

→ This finite resistance region might persist as T → 0 (example of T=0 metallic state)

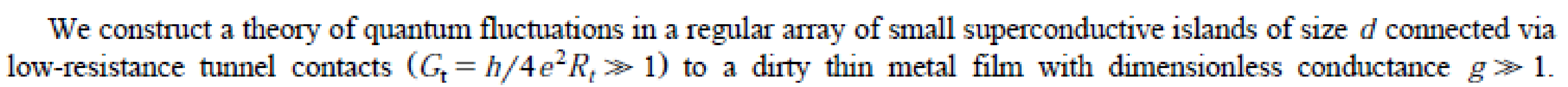
Relation to pseudogap? Unusual metallic properties in other 2D systems?

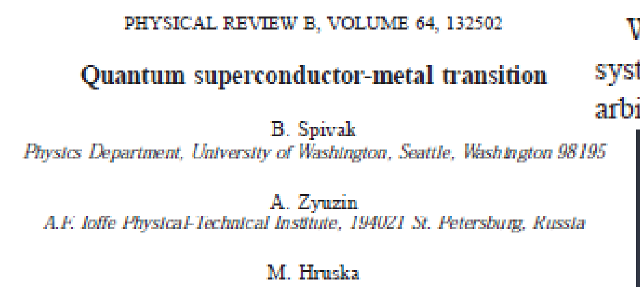
Ongoing work:

- Comparing metallic state to models


Quantum superconductor–metal transition in a 2D proximity-coupled array

M.V. Feigel'man [a], A.I. Larkin [a,b]


We construct a theory of quantum fluctuations in a regular array of small superconductive islands of size d connected via low-resistance tunnel contacts ($G_t = h/4e^2R_t \gg 1$) to a dirty thin metal film with dimensionless conductance $g \gg 1$.


PHYSICAL REVIEW B, VOLUME 64, 132502

Quantum superconductor-metal transition

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M. Hruska
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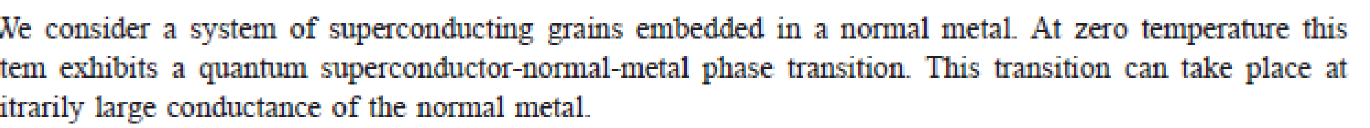
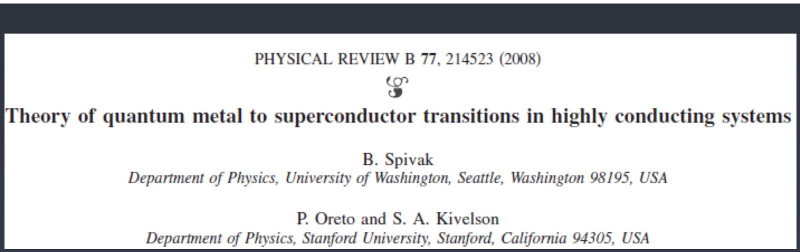
(Received 15 October 2000; published 28 August 2001)


We consider a system of superconducting grains embedded in a normal metal. At zero temperature this system exhibits a quantum superconductor-normal-metal phase transition. This transition can take place at arbitrarily large conductance of the normal metal.


PHYSICAL REVIEW B 77, 214523 (2008)

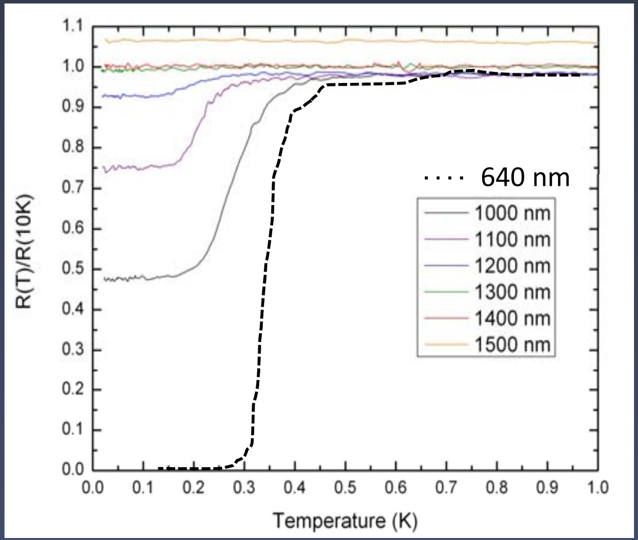
Theory of quantum metal to superconductor transitions in highly conducting systems

B. Spivak
Department of Physics, University of Washington, Seattle, Washington 98195, USA

P. Oreto and S. A. Kivelson
Department of Physics, Stanford University, Stanford, California 94305, USA

- STM & magnetic measurements

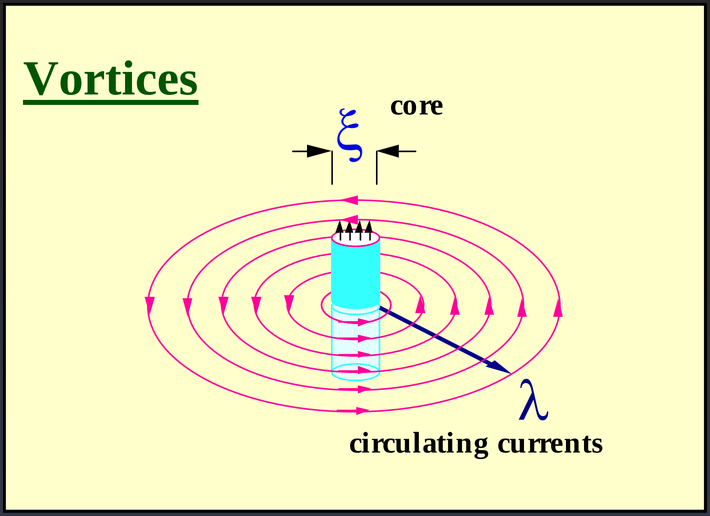
- Studying the T_2 transition to superconductivity: evidence of metallic state, unusual behavior with increased spacing



- Studying Magnetic Field Dependence

Magnetic Field Behavior

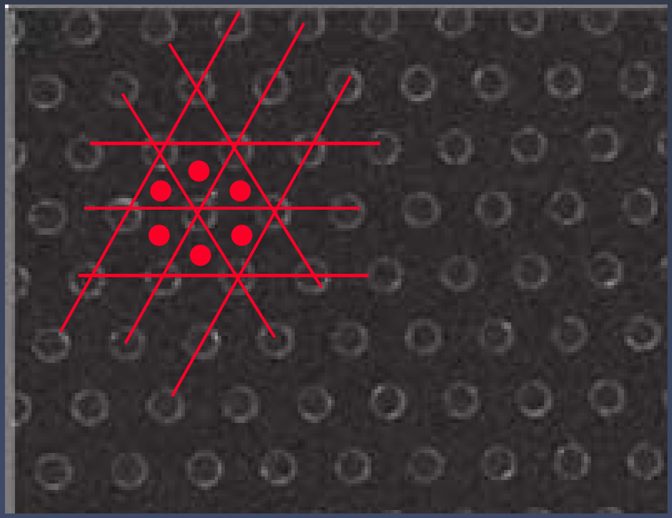
- Magnetic fields oppose pairing
- Fields can penetrate thin film superconductors as vortices



Vortex = circulating current containing one flux quantum, Φ_0 =h/2e

Vortices are “excitations” – can pin in a lattice or in “weak links” of superconductor

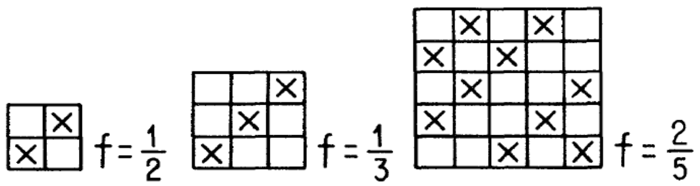
Vortices pinned between islands – Number of vortices depends on magnitude of magnetic field

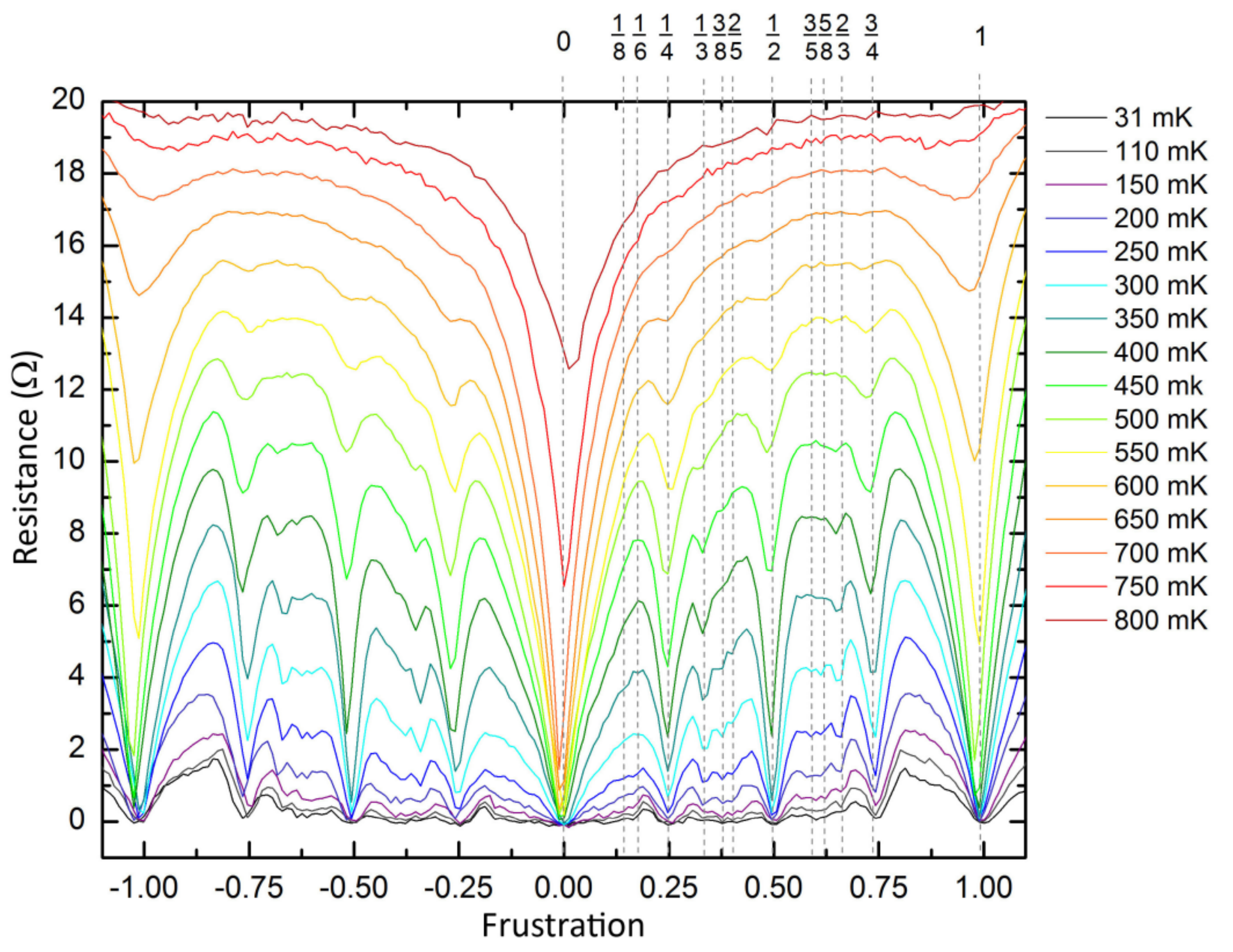


Resistance vs. Magnetic Field: Frustration

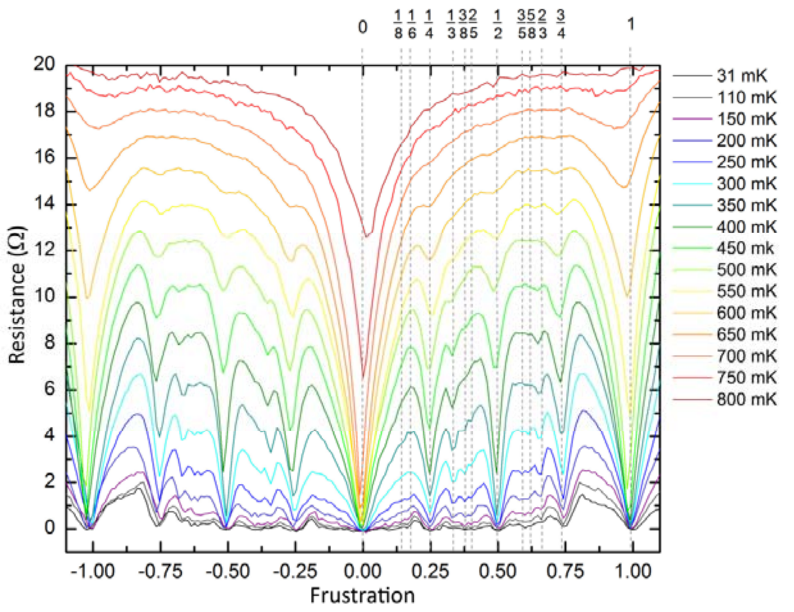
$f = \Phi/\Phi_0 = \Phi_0$ per plaquette

pinning sites at center of each plaquette → low R for f = n/m





Resistance vs. Magnetic Field: Frustration

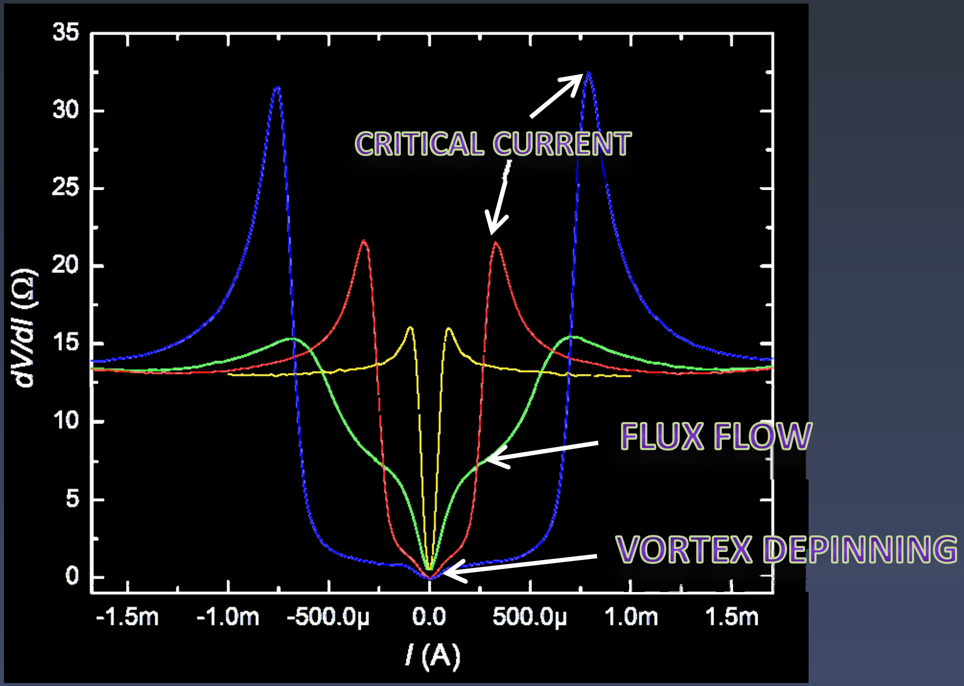


- Phase transitions between vortex states
- Vortex dynamics: collective depinning with applied current

<u>Further ongoing work exploring:</u>

-new lattice configurations

-graphene, topological insulator substrates

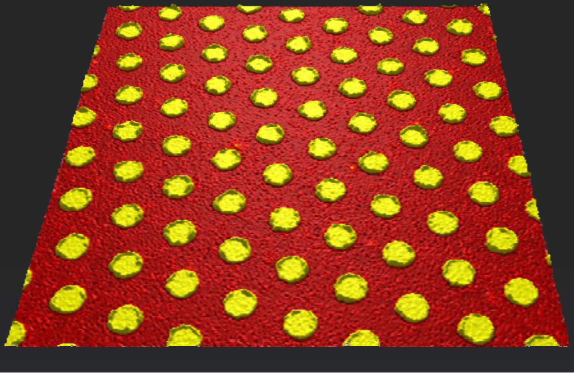


CRITICAL CURRENT

FLUX FLOW

VORTEX DEPINNING

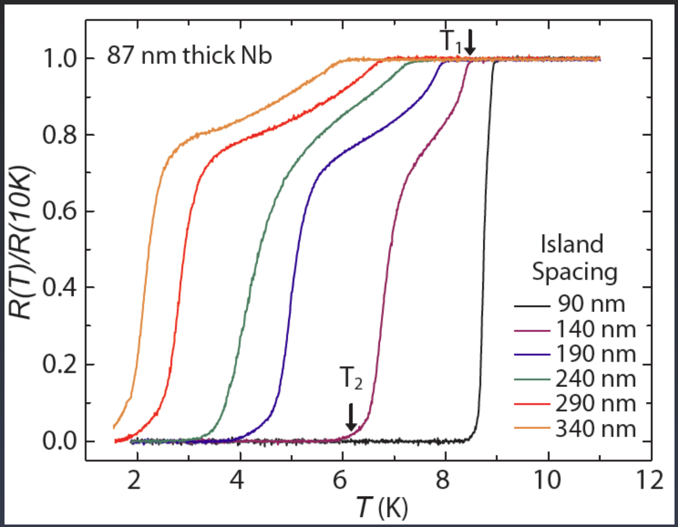
Conclusions



Superconducting islands on metallic substrate = tunable superconducting system

Observation of 2D metallic state, magnetic frustration

Model system for studying parameters relevant to collective behavior



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Serena Eley

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